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OPTICAL ASTRONOMY

Changing Horizons

Colin A. Ronan

With frontispiece and 16 pages of plates

25 diagrams by DAVID WHEELER

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C. A. R.

Preface

WHAT we know of the universe depends upon what we can observe. Our picture is built up from the light, the heat and other radiation that the stars and planets send us. This is our sole source of knowledge, and it is the astronomer's task to make as much use of it as he can. The ways in which he does so depend upon the kind of radiation that he is examining. For convenience he separates this into two parts—optical radiation on the one hand, and radio radiation on the other. Radio radiation is the province of another book in this series, but optical radiation and the story of optical astronomy are the subjects of this book. This means that we shall here be concerned with the universe that we can see, or at least with observations that give us photographs which we can study. It is a story that begins far back in time, and if we are to see the latest results and the future hopes of astronomers in anything like their true perspective, we must sketch something of the efforts of the early optical astronomers. It is with them that we must begin.

COLIN A. RONAN.

1964.

I. Expanding Horizons

FROM the earliest times the sky has fascinated mankind. For thousands of years men have watched the rising and setting of the Sun and Moon, and have mapped the patterns of the stars. But as they did so they found that a few stars wandered in and out among the rest. These wandering stars, or 'planets' as we now call them, were five in number, or seven if we count the Sun and the Moon as well. Their movements formed the main study of astronomers for more than four thousand years.

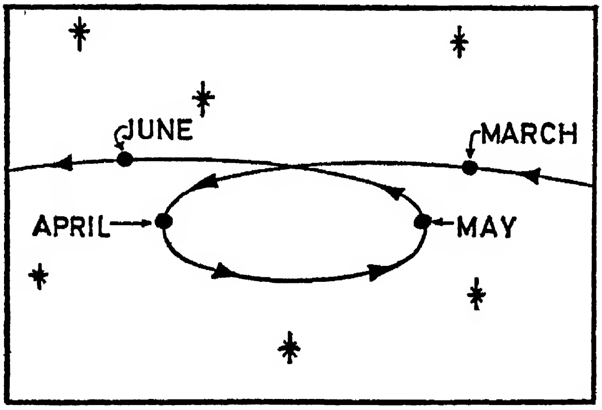


FIG. 1. Apparent path of planet among the stars.

If we observe a planet like Mars or Jupiter in the sky, we find that it does not always travel in the same direction among the stars (Fig. 1). Although it travels from west to east most of the time, now and again it seems to stand still and then for a few days moves in the opposite direction, back towards the west. To the earliest astronomers this was a serious problem. Why, they wondered, should a planet keep stopping in its circuit of the sky? Why should it move backwards for a while, stop, and then move forwards again? And why should it happen only to some planets; why should the Moon and the Sun not do this also?

It was the astronomers of ancient Greece who really began to find an answer. They put forward a scheme that explained the whole universe. We now know that their ideas were not correct, but this is not because of any superiority on our part: it is only because we know certain facts of which they were unaware. They thought that the Earth was stationary because it seemed self-evident that so massive a body must remain fixed. They also

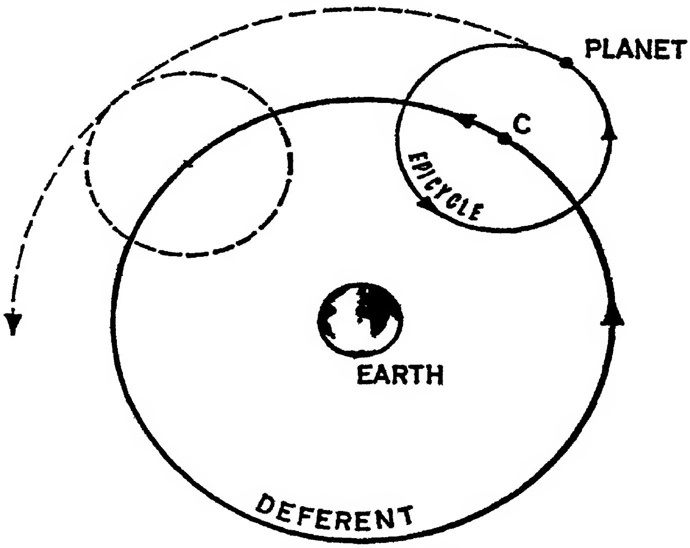


FIG. 2. Explaining apparent path of a planet by using circles. The 'deferent' was so called because it carried (Latin: *defero*) the small circle or 'on-circle' (Greek: *epi*, on; *kuklos*, circle). The planet orbited around the epicycle, and the epicycle orbited round the deferent. The Earth was close to or at the centre of the deferent.

believed it to be at the centre of the universe for the simple reason that we see the stars, the planets, and the Sun and Moon for ever orbiting round it.

In fact, there was another good reason for believing that the Earth was in the centre of the cosmos. Things that fell down or dropped from a great height all moved towards the centre of the Earth. Yet how should they do so if it were not the centre of all things? Still, the Greeks were not blind to other ideas. They considered the possibility of a moving Earth, and even the idea that it spun on its axis once a day. The trouble was that they could find no evidence to support such views.

The Greek astronomers also studied the exact paths in which the planets moved. They decided that their motions must be quite regular and in a series of circles (Fig. 2). They believed that many kinds of evidence supported their view, and for more than two

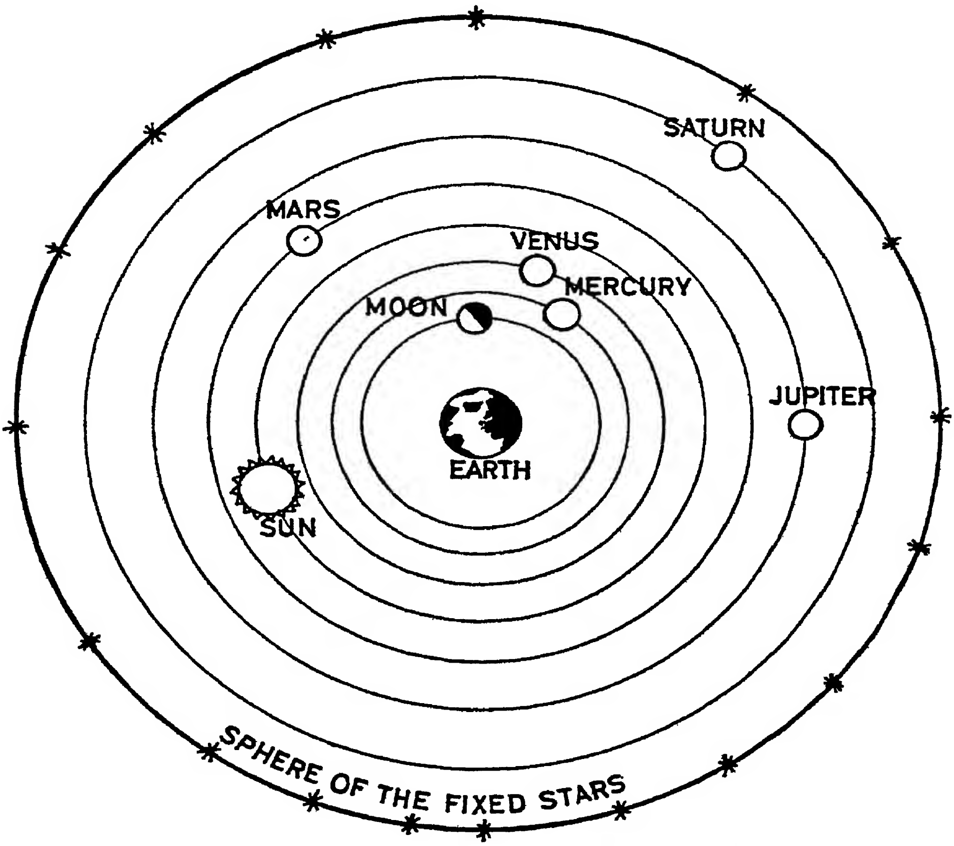


FIG. 3. The Universe as Ptolemy believed it to be—A.D. 150.

thousand years all astronomers agreed with them. The problem of astronomy was, then, to take circular orbits and combine them in such a way that they would account for the backwards and forwards motion of the planets. The Greek astronomers themselves were successful in this, and in A.D. 150 their teaching was summed up and published in a great book by the astronomer Claudius Ptolemaeus, usually known as Ptolemy (*see* Fig. 3). His book was a brilliant explanation of all astronomy. After his death, when the

Roman empire had fallen and the followers of the prophet Mohammed had conquered much of the Near East and the then civilized world, it was translated into Arabic. Since then it has become known by the Arabic nickname of *Almagest* ('The Greatest'). As

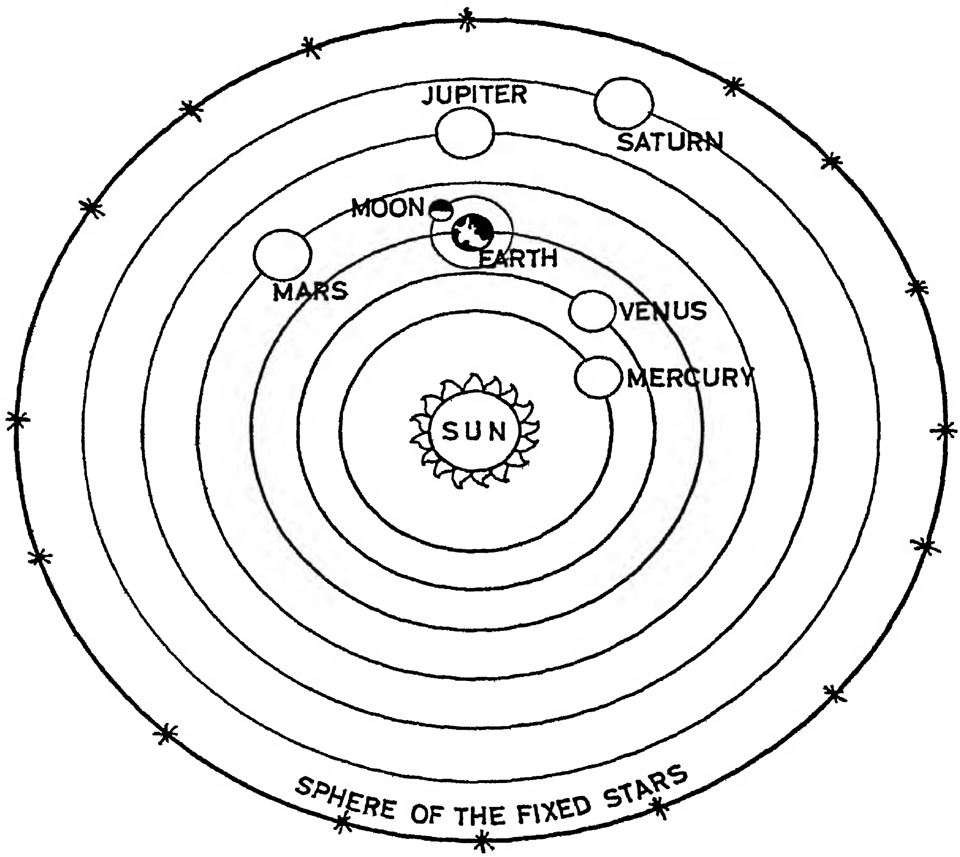
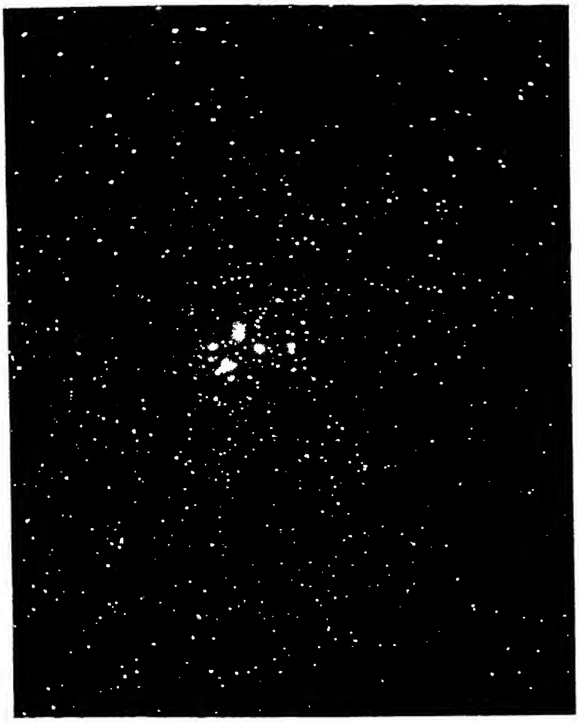


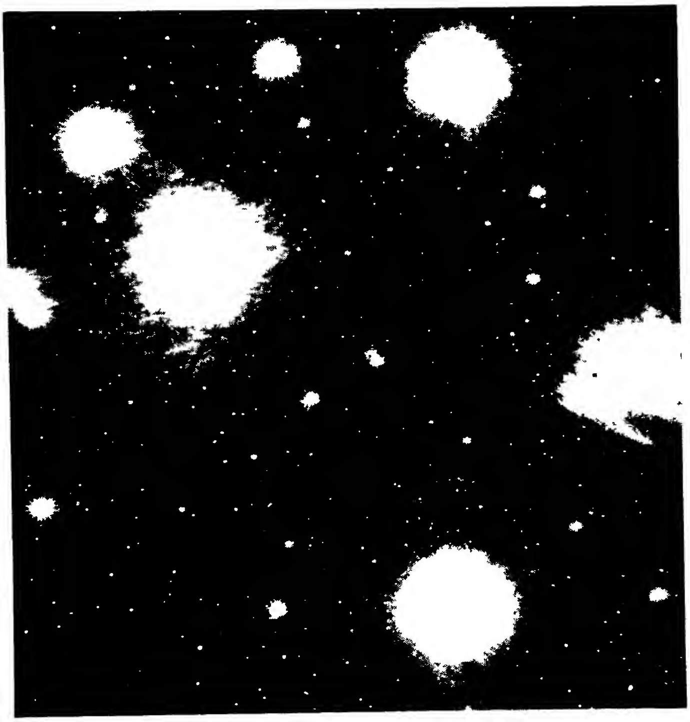
FIG. 4. The Universe as Copernicus believed it to be—1543.

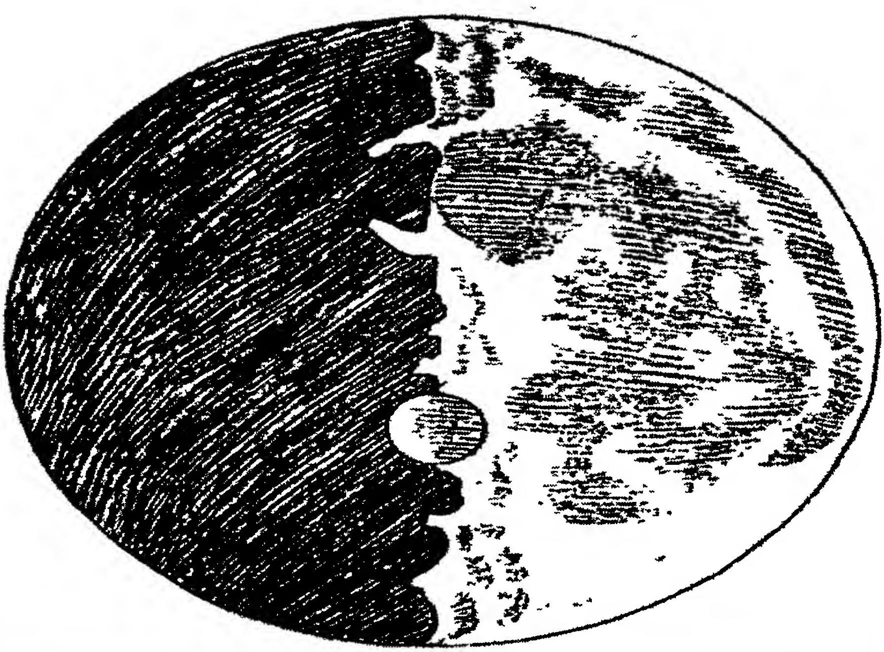
its teachings were not seriously challenged for fifteen hundred years, we can see that its influence on astronomy was immense.

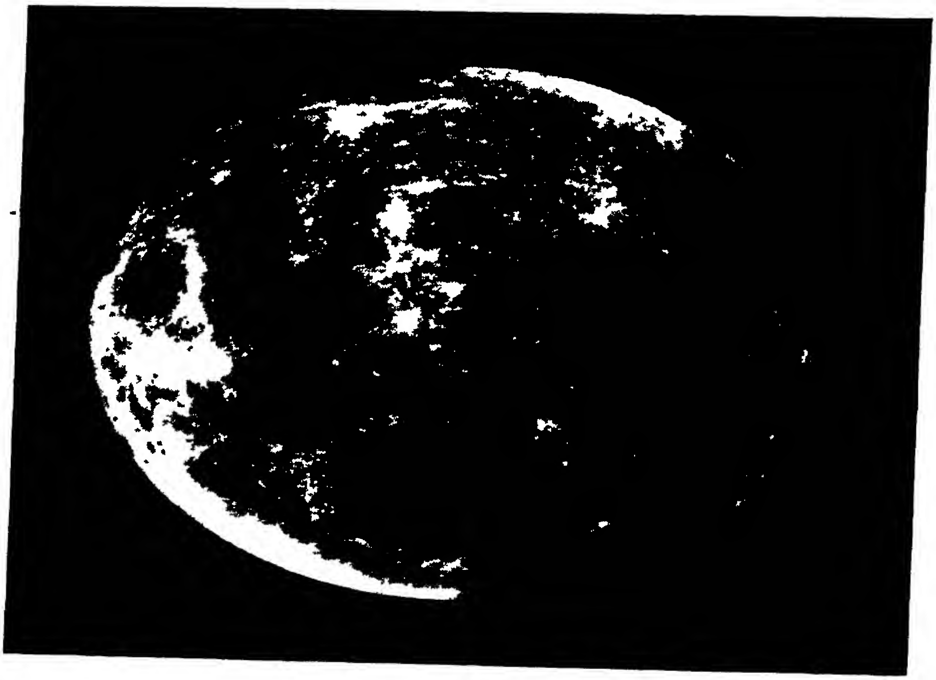
The detailed explanations of the motions of the Sun, Moon, and planets that Ptolemy had given were excellent when he wrote them but, by the year 1500, astronomers were finding them difficult to use. This was because observations which had been collected over the centuries since the *Almagest* was published were



I This cluster of stars (the Pleiades), *left*, as seen by naked eye and, *below*, as observed through a telescope at Lick Observatory.







II *Above*, the Moon as Galileo saw it in 1609 and (*below*) as photographed through a telescope by the British astronomer Dr A. A. Common at Ealing in 1876.

showing that Ptolemy's theories did not exactly satisfy the facts. The problem was what could be done.

It was in 1543 that the first great step forward was taken. In that year, as he lay dying, the Polish cleric Nicholas Copernicus had a copy of his book *On the Revolutions of the Celestial Spheres* put into his hands. This book was the result of many years' study, and in it he proposed that astronomers should accept that the Earth revolved about the Sun. Certainly this idea would make it

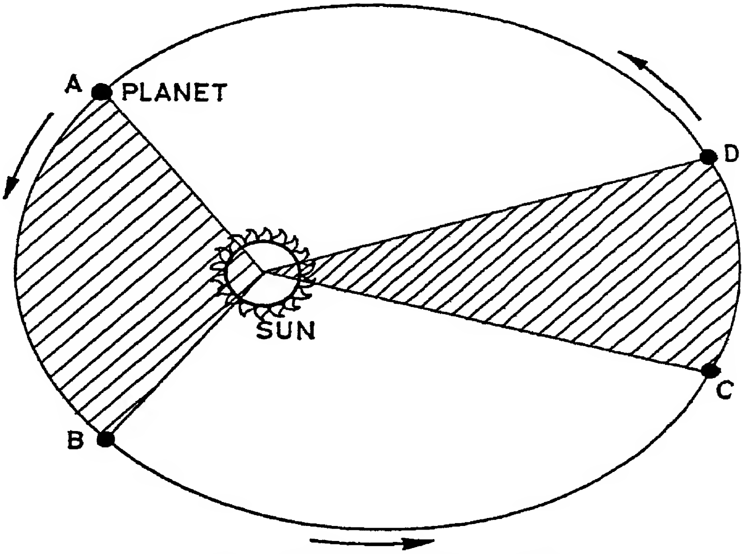


FIG. 5. The path of a planet as explained by Kepler. He found that a planet moved in ellipse and at a changing speed. The planet moves from A to B in the same time that it takes to move from C to D, so that the areas ABSun and DCSun (shown shaded) are equal.

easier to work out future positions of the Moon and even of some of the planets, and so many astronomers accepted the view, at least as far as their mathematical work was concerned (Fig. 4).

Copernicus still used the regular circular orbits of Ptolemy, and it was not for another seventy-five years that this idea was put aside. Then Johannes Kepler discovered that oval orbits fitted the observed motions of the planets best of all. So it seemed that the Earth, the Moon, and the other planets orbited the Sun in paths that were slightly oval (Fig. 5). Yet why should they do so? Why should they orbit in an oval path, or even in a circular one for that

matter? Many astronomers tackled this question and finally, in 1687, Isaac Newton published an answer in his great book *Mathematical Principles of Natural Philosophy* (*Philosophiae Naturalis Principia Mathematica*). Building upon the work of others who were struggling with the problems of planetary motion, Newton put forward his theory of universal gravitation. This was a brilliant idea. It explained how the Sun pulls the planets and causes them all to orbit round it, and how the Earth pulls the Moon and keeps it in orbit. But it did more, because Newton was able to prove mathematically that such a law fitted exactly all observations of the planets and the orbit of the Moon. This was the coping-stone of his achievement, and brought wide acceptance of his ideas in the years that followed. Newton also showed that the same law that fitted the motions of the Moon and planets also fitted exactly the motion of bodies on Earth. This meant at last one law for all moving bodies, wherever they might be. After more than two thousand years, astronomers had come to the edge of one horizon—the horizon of planetary motion. Yet, as they did so, a new horizon was opening out before them.

II. *The Telescope Probes Space*

WHAT kind of body is the Moon? What are the planets really like? What is the Sun made of? What are the stars? These questions have puzzled astronomers for thousands of years. Because the planets and the stars seem always to have existed, astronomers had come to the conclusion that they were all bodies that never grew old or decayed. They were perfect and eternal. However, in 1609 these ideas were shattered. The telescope was invented and, for the first time, astronomers could study the Sun, the Moon, and the planets in detail.

Who actually invented the telescope no one knows. The thirteenth-century English philosopher Roger Bacon is supposed to have known the optical principles, and even claimed that Julius Caesar used a telescope on his invasion of Britain in 55 B.C.! But this is more legend than fact, and not until 1560 do we find anyone else credited with such an instrument. About this time another Englishman, Leonard Digges, is supposed to have made a telescope. Yet even this is uncertain, and it is to three Dutchmen that the credit is most probably due. In October 1608 Hans Lippershey and Zacharias Jansen, who lived in the city of Middelburg, and James Metius of Alkmaar, each demanded patents for the invention. All three were spectacle makers and it is impossible now to decide who was really the inventor. Of one thing at least we can be certain—by 1608 telescopes were in use in Holland. As can be imagined, they caused much interest, and by the next year news of them had reached the astronomer Galileo in Italy. Although the facts he received were meagre, Galileo settled down to work out the principles of such a device. In fact what he really did was to re-invent the telescope, and within a few days of hearing the news from Holland he had designed and built a successful instrument.

It was Galileo who first seriously applied the telescope to astronomy and began a series of careful observations with it. The

results were without parallel in the whole history of astronomy. For the first time man was able to study the Moon and the planets in detail and to see stars that no one had ever seen before (Pl. I). His knowledge of the universe began to grow by leaps and bounds. There seemed no end to the wider horizons that were opening out before him.

Every new observation brought with it a host of novel ideas. Some of these so upset Galileo's contemporaries (who wished to keep rigidly to the old astronomy) that in the end the authorities were persuaded to forbid Galileo to teach the new theories. The trouble was that, in observing the Moon, Galileo found that its surface was pitted with craters, and that there were mountains and

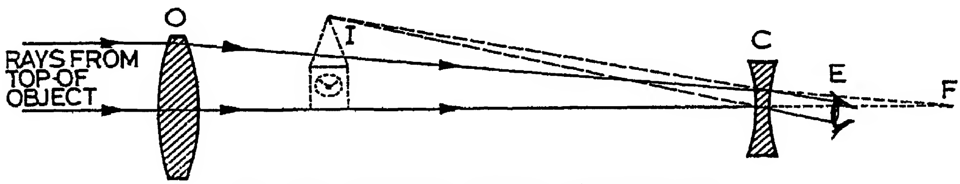


FIG. 6. Galileo's design of telescope.

valleys (Pl. IIA). Admittedly he thought that the large, dark, flat plains were seas. But no matter—he had discovered that the Moon was a body just like the Earth (Pl. IIB). This hit hard at the old idea of the Greeks that celestial bodies were made of something quite different from any substance found on Earth. Galileo saw with his own eyes that this idea was untrue. Again, when he observed the planet Jupiter, he found that there were four bright satellites that orbited about it. Now one of the arguments against Copernicus's idea of a moving Earth was that the Moon would be left behind, but here the telescope showed that this did not happen —Jupiter's moons remained with him even though he orbited round the Sun. So the telescope brought about what was really a revolution in astronomy.

Galileo's success soon became widely known and many astronomers began to use telescopes. The trouble with Galileo's telescope was that it magnified only a very small portion of the sky. This was because of the optical design which used a concave lens for the eyepiece. It was certainly a sound enough design in principle, as Fig. 6 shows. The front lens O (usually called the 'object-glass' because

it faces the object being observed) collected the light from the distant scene. This light is refracted inwards to the point F—the focus of the lens O. At F we obtain a small, bright inverted image. Now the purpose of a telescope eyepiece is to magnify this image. Galileo used a concave lens C which refracted the rays outwards, and so gave an image I to an observer's eye at E. Because the rays spread outwards, only a portion of all the incoming light is used for making the image and we see only a small, but magnified, part of the scene.

A different eyepiece was suggested by Johannes Kepler, with whom Galileo used to correspond. Kepler's design is shown in Fig. 7. The eyepiece, like the object-glass, is convex, and gathers

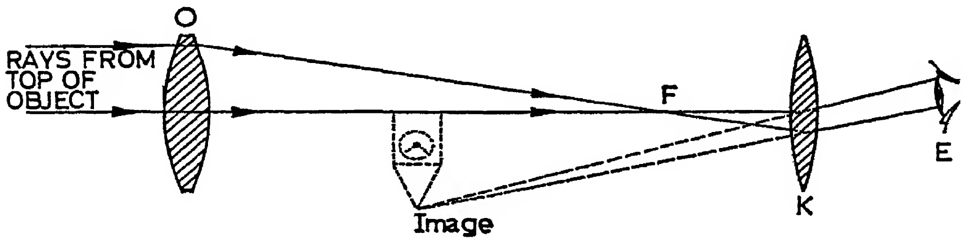


FIG. 7. Kepler's design of telescope.

all light into the eye. A larger area of the scene can be observed, but the image I is now upside down. However, astronomers do not trouble which way up the image appears, for stars look like small dots of light and the Moon, Sun, and planets are round—so an inverted image is no disadvantage. Kepler's design was the more widely adopted, and telescopes of this kind were soon to be found all over Europe. To begin with they were not very efficient, mainly because the images seen in them all possessed coloured edges. This defect was due to the fact that a single lens used as an object-glass cannot bring light of every colour to focus at the same point. It was not until 1757 that the optician John Dollond successfully constructed an object-glass to overcome the error by using two lenses, each made of a different kind of glass. Fortunately, however, the coloured fringe did not damp enthusiasm, and many observations of star positions and of the Moon and planets were made.

Isaac Newton, who was greatly interested in optics, suggested a quite novel way of overcoming this problem. This was to use a

mirror instead of an object-glass to gather the light and bring it to a focus. Because it reflected light at its surface and did not allow the rays to pass through it, a mirror could not introduce coloured fringes. In 1666, the year of the Great Fire of London, Newton built an instrument of this kind. Fig. 8 illustrates Newton's design and shows how he used a small mirror to bring the light out to the side of the telescope for greater ease in observing. In theory, Newton's reflecting telescope was superior to the refracting types of Galileo or Kepler, yet astronomers did not adopt it. Instead they continued to use the refracting telescope, minimizing the optical faults by using object-glasses of immense focal length.

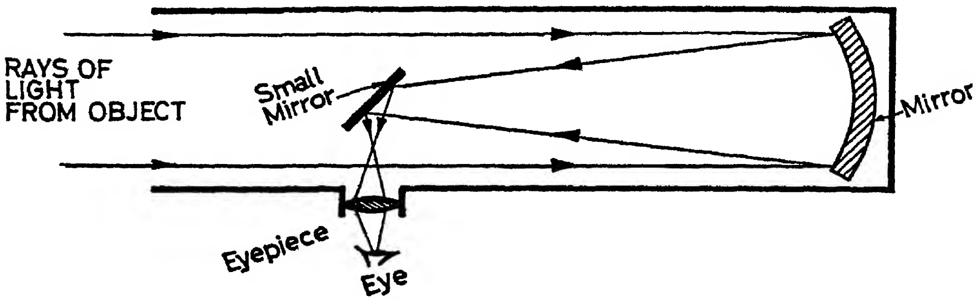


FIG. 8. Newton's design of reflecting telescope.

The reflecting telescope came into real use only in 1774, when William Herschel began to make and use instruments of this kind. Although a professional musician, he gradually became so interested in astronomy that in the end he gave up his musical career. However, before this happened he made a unique discovery with his telescope. On the evening of 13 March 1781 he found a new planet in the heavens, later called Uranus. From time immemorial, mankind had known of the five planets Mercury, Venus, Mars, Jupiter, and Saturn—since these can be seen without a telescope. But now a new and important member of the Sun's family of orbiting planets had been discovered, and it was suddenly clear to astronomers that they must think again about how far the Sun's influence extended into space. A year later Herschel received a royal pension, and forsook music for astronomy.

Herschel had an incredible flair for making telescopes, and he constructed larger and larger instruments to gather more and

more light from the depths of space. His greatest telescope had a tube 40 feet long, with a mirror almost 48 inches across, and weighing nearly a ton (Pl. IIIA). Indeed, this and another of his instruments were large enough for him to dispense with the little flat mirror used by Newton to bring the light out to the side of the tube. In these two Herschel placed an eyepiece at the front end of the telescope and he observed by looking straight down the tube.

The power of a telescope to penetrate into the depths of space depends mainly upon its size. The larger it is, the dimmer are the objects whose light it can detect. Herschel's immense telescopes were by far the largest then in existence. Stars still appeared only as tiny dots of light, but thousands more could be seen than ever before. Herschel surveyed the whole sky visible from north of the equator and discovered many new and strange facts. He found that some stars were always to be seen in pairs, orbiting round one another. This is important, for it shows astronomers that gravitation definitely exists right out into the depths of space.

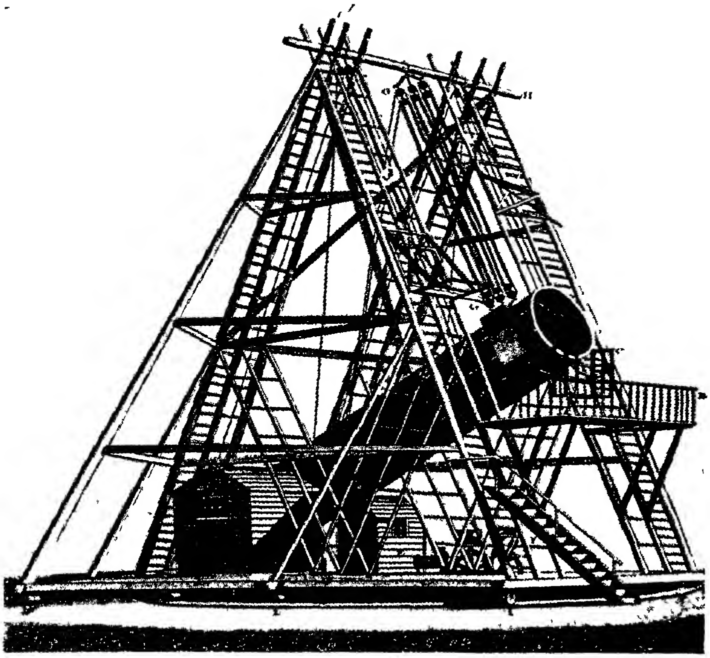
The telescope had allowed Herschel and other astronomers to form a scientific picture of the whole universe and to discover how the stars move and how they are distributed in space. This is difficult to do at the best of times, but in Herschel's day it was an almost impossible task because no one knew the distance of even the nearest star. However, he did manage to obtain some results and came to the conclusion that the stars did not extend equally in every direction. Yet he was not entirely satisfied, and spent much time in studying tiny hazy patches of starlight called nebulae. Were they clouds—probably of gas—as they seemed to be, or were they really just clusters of stars which his telescope was not big enough to separate out? This was a serious question. The problem was of great importance for deciding the nature of the universe, but its solution needed telescopes more powerful than Herschel's.

Newton and Herschel made their reflecting mirrors of speculum metal—an alloy, mainly of copper and tin, to which small quantities of other metals like antimony were added. It was brittle and it tarnished quite quickly, but in 1845, after experimenting for nearly twenty years, the Earl of Rosse was able to cast this brittle metal into an immense mirror six feet in diameter. Mounted so that it could move in a north–south direction, and supported between two brick walls (Pl. IIIB)—it had to wait for the Earth's

rotation to give it an east-west movement—this giant instrument had four times the space-penetrating power of even Herschel's largest telescope. With it Rosse opened up new horizons to the astronomer and was the first to see what we now call spiral galaxies. At the time Rosse did not know what they were and nor did other astronomers, for no one else had a telescope large enough to see them. Many of them were objects that Herschel had seen and classified as nebulae, but now a number could be seen to have a strange spiral structure. Were these collections of gas or clusters of stars, and how far off did they lie? As so often happens, new observations bring to light new questions; astronomers now knew the universe was far more strange than had ever been realized, and they found many more puzzles facing them. Rosse had shown the existence of strange nebulae, but it was clear that still greater space-penetrating power was needed. What is more, astronomers found that to tackle these problems they just had to discover the real distances of the stars, a task that required measurements of incredible precision.

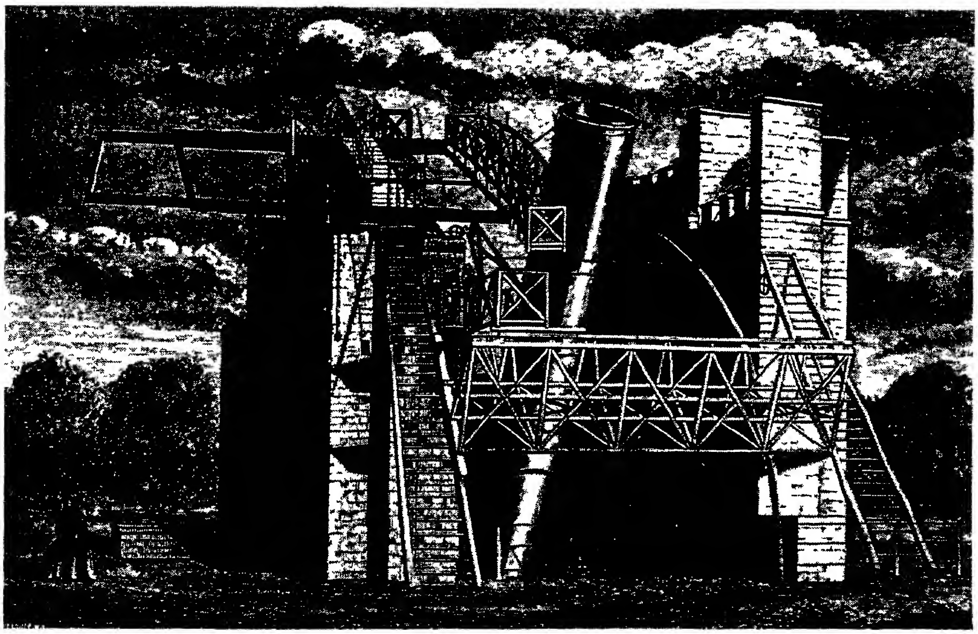
These challenges had their effect, and success came in three ways. In the first place three astronomers made a break-through into the problem of stellar distances. In 1838 success was announced by Friedrich Bessel, who was using a refractor of very fine construction ideally suited to precise measurement. He measured the distance of the close dim star known by its number in star catalogues as '61 Cygni', obtaining the incredible distance of 558 million miles. Surprisingly enough, within two months another astronomer, Thomas Henderson, also determined a star's distance; and the great observer F. G. W. Struve made his own measurements soon after. But neither his work nor that of Henderson was as accurate as Bessel's. These really careful measurements showed that the distances of the stars were surprisingly vast. Millions of millions of miles were needed to express them. It was at last possible for astronomers to gain a truer idea of the size of the universe and its contents, and as the years went by the details were filled in with increasing speed and precision.

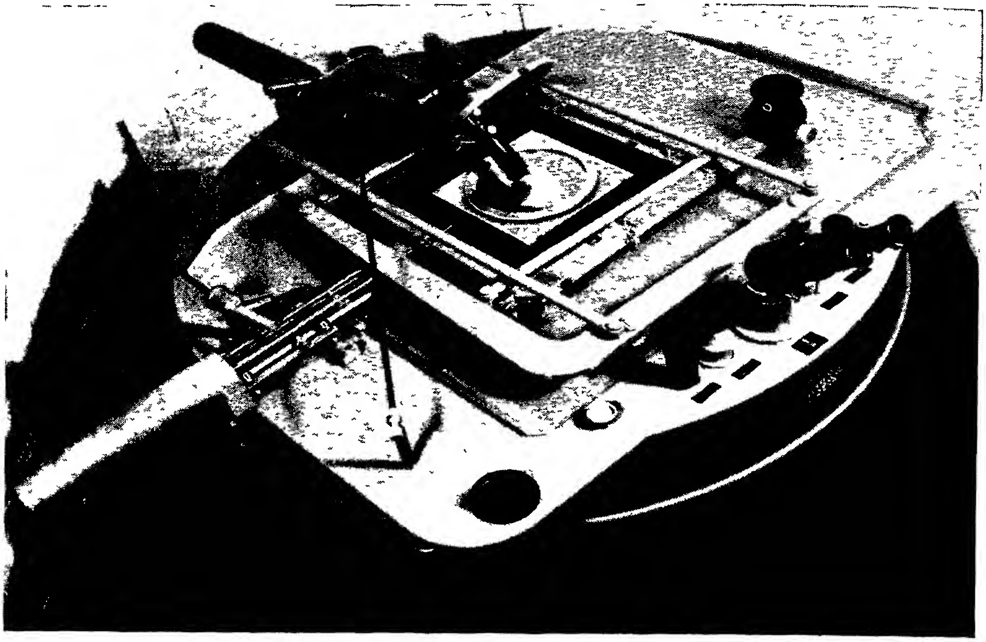
The second way in which the challenge to probe the universe has been met is by building larger and larger telescopes. In the United States big reflecting telescopes were made with silvered glass mirrors to replace the speculum metal, and in 1919 a giant



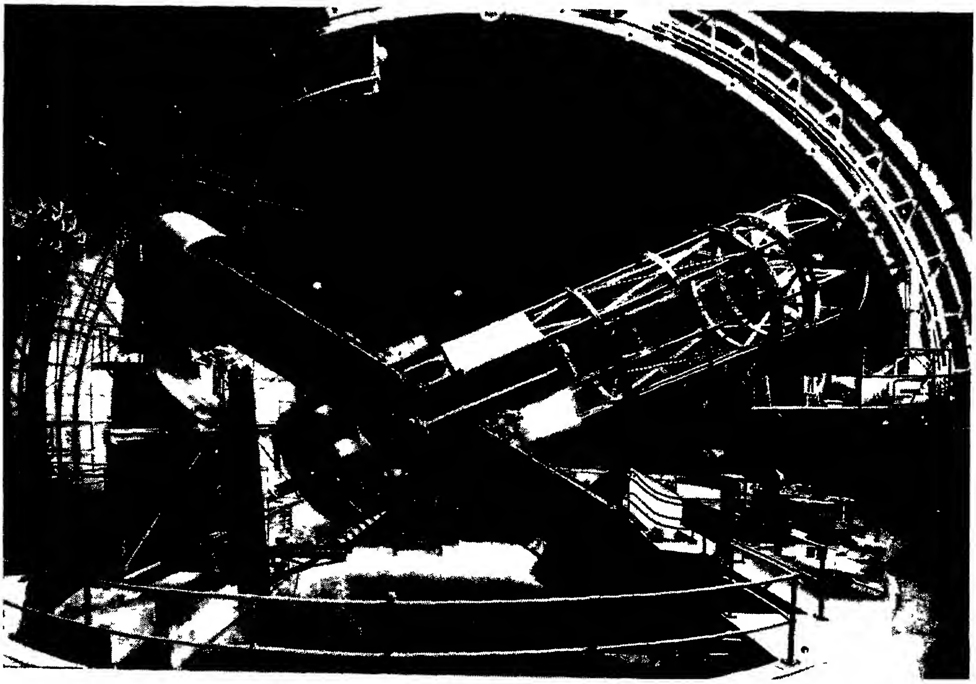
III Herschel's 40-foot telescope.

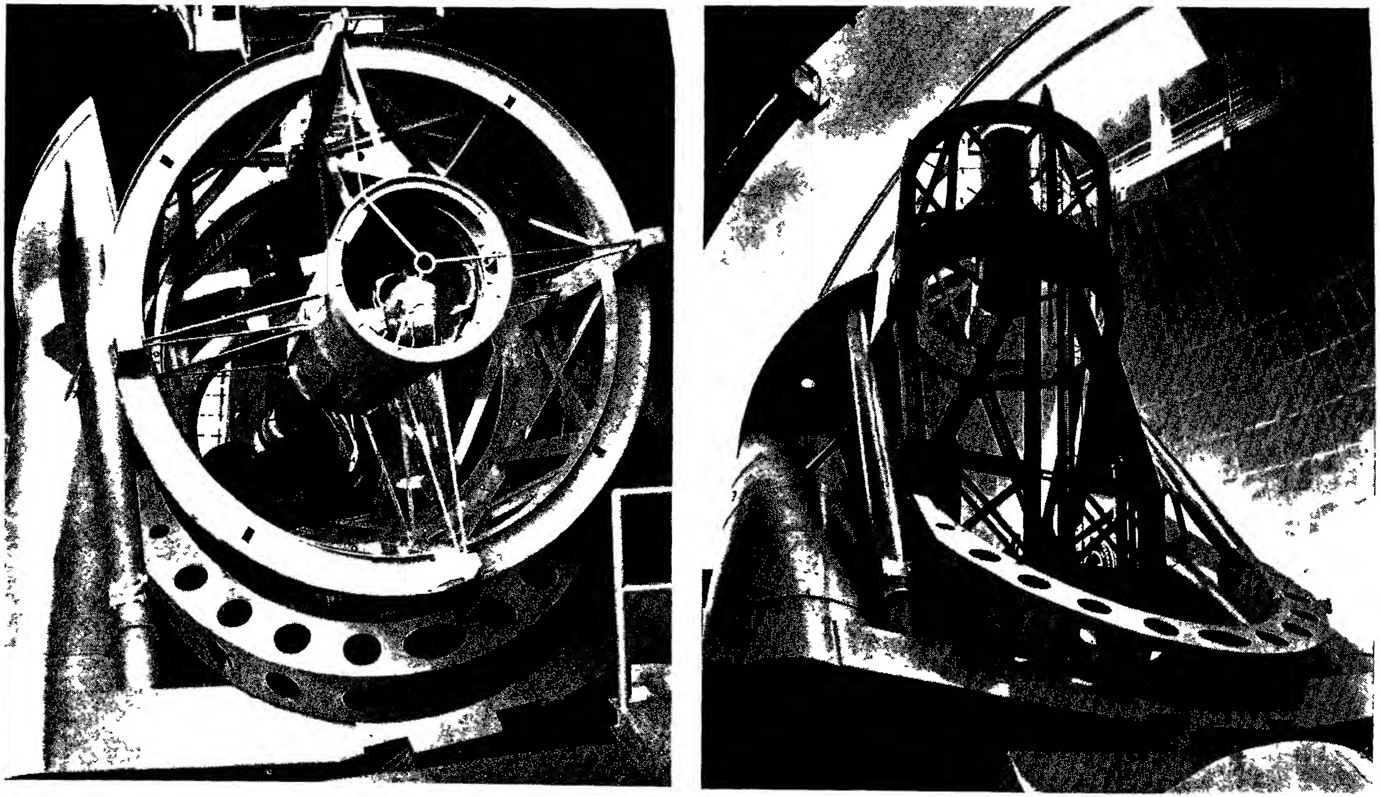
The Earl of Rosse's giant reflector.



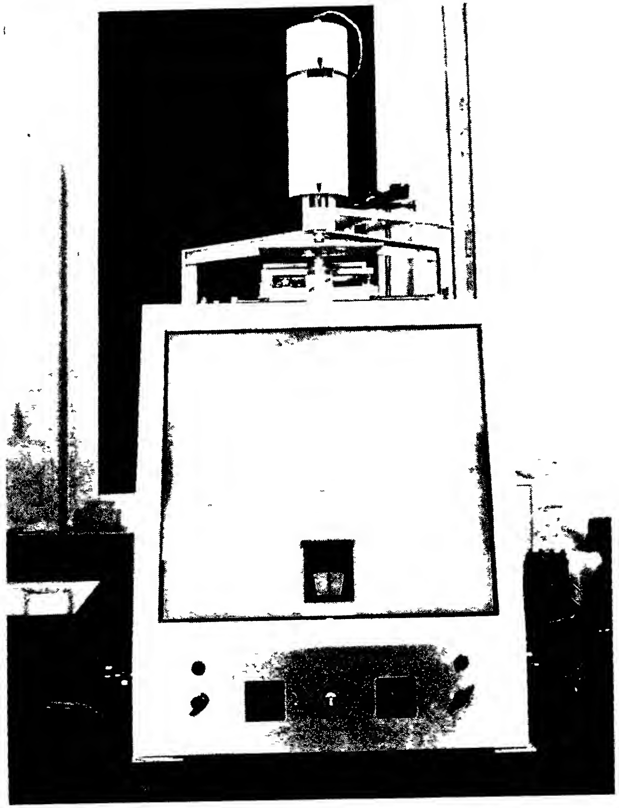


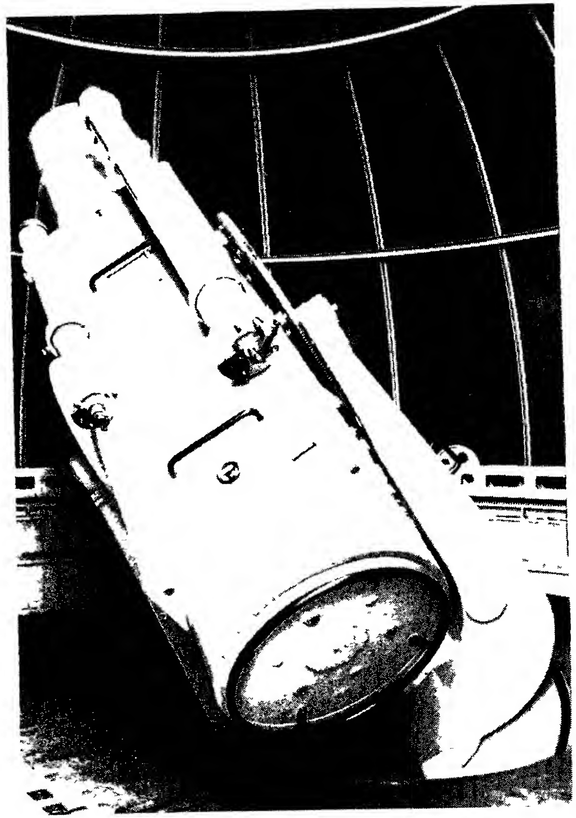
IV *Above*, plate-measuring machine at Cambridge University Observatories. The plate is inserted at the centre and the position of the objects read off by the binocular microscope on the right. *Below*, the 100-inch telescope at Mount Wilson Observatory.





V Two views of the 200-inch telescope at Mount Palomar Observatory.





VI *Left*, an electronic microphotometer for measuring the brightness of stars from photographs. The photographic plate is put under the lamphouse at the top and the star is displayed on the screen. The knobs at the front of the machine are for adjusting electronic circuits. ***Right***, the Schmidt 24-inch telescope at Cambridge.

100-inch telescope came into use in California (Pl. IVB). Its light-gathering power was at least five times as great as Rosse's big telescope, and it was fitted to a most elaborate mounting so that it could be pointed to almost any part of the sky. What is more, it could track the stars automatically as they appeared to move across the sky. This was vital if the telescope was to be used for taking photographs—which had, by this time, really come into their own. Indeed, astronomers were finding photography an indispensable aid to probing space, and there was no doubt that the 100-inch telescope should be used almost entirely as a giant camera. A photographic plate can respond to light that is far too dim to affect the human eye, so a telescope used as a camera can observe dimmer objects and so penetrate farther into space than it could do if used only as a visual instrument. This is why what is at present the world's largest telescope, the 200-inch at Mount Palomar in California (Pl. V), has never been used visually for any scientific work since its completion in 1948. The stars still show as tiny dots on its photographs but, considering their distances, this is not surprising. Photography is, in fact, the third way in which the challenge of probing the universe was met.

The whole universe, or such parts of it as can now be seen in optical telescopes, is much vaster and far stranger than anything ever imagined by even Galileo or Newton. The Sun, so important to us and to the other planets that orbit round it, is no more than an ordinary star. It is only one of some 30,000 million stars which are collected into a round island of dust, gas and stars that we call the Milky Way or the Galaxy. The Galaxy, rather like a catherine-wheel in shape, is of vast extent, being so big that light takes more than 20,000 years to travel through even the thinner part, and at least 100,000 years to pass from one edge to the other. When we remember that light travels 186,300 miles every second, and that there are more than 31½ million seconds in a year, we can see that the size of the Galaxy is almost too large for us to comprehend. Moreover, our Sun is not situated at the centre, but lies closer to the outer edge and in one of the spiral catherine-wheel arms.

The Galaxy itself would make an amazing enough universe, but it has now been found that it is only one of countless millions of such spiral 'islands'. Scattered throughout space, sometimes singly but often in groups or clusters, these other galaxies lie

at immense distances. From the nearest, light takes about two million years to reach us, but, from the farthest so far photographed, light has taken more than 6,000 million years. Even so, we know that we have not probed the depths of the universe. Our horizons are still expanding as our means of observing change and improve.

III. *Measuring the Stars*

TO DISCOVER the nature of the stars and to probe the depths of the universe, astronomers must carry out the most precise measurements. In fact, the accuracy they achieve is remarkable, and almost as surprising as the distances of the stars and galaxies that they measure. We can gain some idea of the precision required if we consider for a moment measuring the distance of our nearest neighbour in space, the Moon.

As we cannot walk to the Moon and find its distance by a tape or chain, measurements have to be made indirectly. Astronomers do this by using a system very similar to that practised by surveyors—the system of 'triangulation'. This method is really a measurement of distance by angles and, as we shall see, is capable

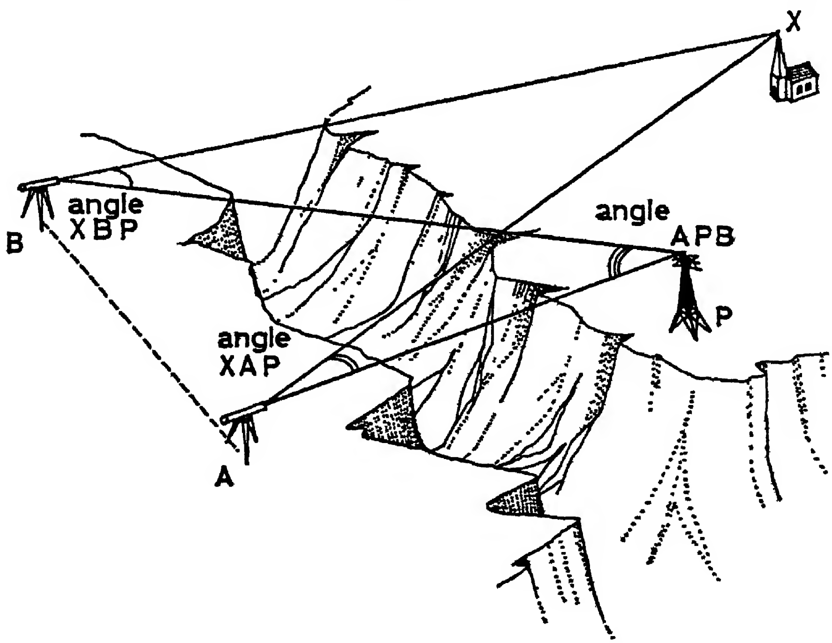


FIG. 9. Surveying by 'triangulation'.

of very great accuracy. Its principle can best be seen if we imagine one of the ways in which a surveyor can determine the distance of a point P (Fig. 9) that he cannot actually reach from his position A. He marks the position of A and then measures the angle that P makes with some more distant object, say, a church steeple at X. He finds, in fact, the angle between X and P (the angle XAP). Now he moves his instruments to another place, B. He measures the distance from A to B and then measures the angle between X and P; this will, of course, be the angle as he now sees it from B (the angle XBP). So, in the end, the surveyor knows the distance A to B and the angles X to P as seen from A and B. With these he can find the angle at P (the angle APB) and, by using trigonometry, he can work out the distance of P itself from the line AB. Thus, without ever going to point P, he can measure its distance.

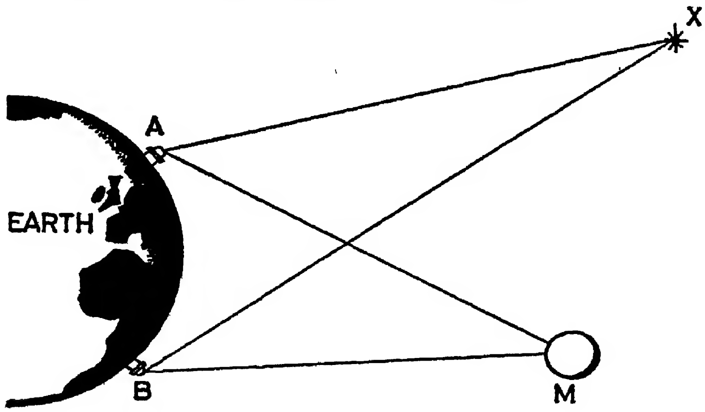


FIG. 10. Measuring the distance of the Moon.

To measure the distance of the Moon, astronomers use a similar method. The points A and B have to be as far apart as possible to give a satisfactory result, and two observatories usually co-operate. In Fig. 10 these are again shown as A and B. For distant objects, in place of the church spire X, the observatories use a star. This procedure gives the angle at the moon, M. This is equivalent to the angle P found by the surveyor, and it is known as the 'parallax' of the body being observed. In this case then M is the parallax of the Moon. The average distance of the Moon from us is about 239,000 miles and therefore the parallax is fairly large, being almost one degree. However, the error allowable in the

observations is small, because a mistake of even one second of arc (1″, or $\frac{1}{3600}$ of a degree) will give an estimate of distance that is incorrect by about 100 miles. It is here, then, that the astronomer's demand for extraordinary accuracy comes in, for 1″ is indeed a very small angle. It is in fact so tiny that it is equivalent to the size of a pinhead at a little more than 225 yards, or a man as seen at a distance of more than 700 miles—angles that need some precise measuring even to detect! Yet 1″ is not the limit of the astronomer's precision, and new techniques have now made it possible to measure angles that are correct to at least $\frac{1}{200}$ of this amount. How this is achieved is quite simple in principle.

Suppose we wish to measure the relative positions of two stars to the greatest possible degree of accuracy. Our first task is to take a photograph of the stars themselves. As with all work of this kind, glass photographic plates rather than films are used, because they are more likely to keep their exact shape during all the various processing that they have to undergo after exposure in the telescope. When the photograph has been taken, processed and dried, it is placed in a plate-measuring machine. A modern instrument of this kind is shown in Pl. IVA. It consists of a special table in the centre of which is a framework to hold the plate being examined. This plate can be moved in two directions, set exactly at right-angles—to the left and right, and forwards and backwards. The operator has the movement of the plate under his complete control, and he views the star images through the binocular microscope at the front of the instrument. He sees them against a background of squares, as illustrated in Fig. 11(*a*). This is because a glass sheet with squares ruled on it is bound next to the plate and the two are put into the measuring machine together. As a result, the operator can measure the star positions with reference to the corner, 0, of a square. In fact it is all rather like measuring the positions of places on a map (Fig. 11(*b*)). Just as we can say that the position of Gerrard's Cross Station is 1·5 units to the right of 0, and 0·8 units above it, so we can say that the position of star A from 0 (Fig. 11(*a*)) is 0·8 right and 0·5 up. In this way the operator measures the distances from 0 of the stars A and B, and of any other he wants. He can then find their distances from each other. The measuring microscope allows him to measure the star images correct to within a thousandth of a millimetre, and as he knows

what angle in the sky this distance on the plate represents, he can find their separation to the really precise degree mentioned.

Although this is the way that the measurements are carried out in principle, all kinds of precautions have to be taken to ensure that a host of errors does not creep in. For instance, there may be a little looseness in the moving plate-holder in the measuring machine—if so, this will give an error. Or the plate may not be squarely in its holder—at least, not to within a thousandth of a millimetre—and even if it is not loose, the plate-holder may not

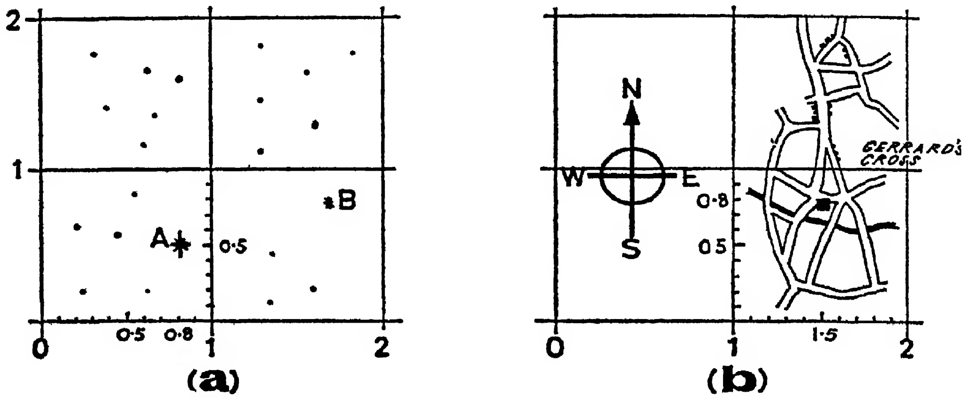


Fig. 11. Star and map positions.

run in directions that are *exactly* at right-angles. Then, again, the photographic emulsion may not have dried evenly all over and it may be stretched more in one direction than in another, the plate itself may not have been mounted quite squarely in the telescope, and so on. There are, in fact, many possible sources of error, and the astronomer has to make his measurements more than once on a plate if he is to eliminate them. In practice, then, the precise measurement of plates is far more difficult than it might appear.

When Bessel made his measurements of star position to obtain parallax, he did not have photographic plates to work with, and he had to make his measurements directly at the telescopic eyepiece. But this method simply cannot give such precision as is obtained with a photograph and a plate-measuring machine, and these are now always used in parallax work and other studies requiring precision measurements of this kind. Yet, accurate though the new methods are, they are very limited in the distances they can

measure. We can see why if we look again at the triangulation principle. Look at Fig. 9; it will be clear that the greater the distance between the observing positions A and B, the greater will be the difference between the angles XAP and XBP, and so the greater the angle at P. In other words, the farther A is from B, the larger is the parallax. If we can measure correctly only angles of not less than $\frac{1}{200}$ of a second of arc, then there is a limit to the distance at which P can lie if we are to measure it satisfactorily. This limit depends on the length of A to B.

How far apart can we spread our observing positions? If we had one at one side of the Earth's equator and the second at the other, then the distance between them would be the diameter of the Earth, that is almost 8,000 miles. Yet this would only allow measurements of distance up to about 160,000 million miles with even tolerable accuracy, and although this seems a very long way it is still not as far as the nearest star! So observations made using the diameter of the Earth as a base-line are no help. But, fortunately for astronomers, the Earth orbits round the Sun once every year, and in consequence two observations made six months apart will give measures made first at one side of the Earth's orbit and then at the other (Fig. 12). The astronomers' base-line becomes the diameter not of the Earth but of the Earth's orbit round the Sun. This is the much larger distance of 186 million miles, and provides a useful stepping-stone into space. Distances measured in this way can extend out to some 2,400 million million miles, and take in a considerable number of the nearer stars.

Of course, figures like the one just given are cumbersome and, to a great extent, meaningless. Living on a planet like the Earth, with a diameter of but 8,000 miles, we simply cannot visualize a distance of this kind. If we are to gain a proper understanding of the universe, we must find something other than miles with which to work. Astronomers have found two satisfactory methods. One is to express distances in angles because, as we have seen, this is the way in which distances are measured. An object that lies so far away that its parallax is one second of arc is said to be at a distance of one 'parsec' (an omnibus word of *par*allax and *sec*ond). An object with a parallax of one tenth of a second of arc is at a distance of ten parsecs, and so on. This term and its multiples—kilo-parsec (1,000 parsecs) and mega-parsec (a million parsecs)—are

often met with in astronomical literature and it is as well to know what they mean.

Nevertheless the most satisfactory way to gain an idea of astronomical distances is to use the 'light-year'—the distance light travels in one year (about six million million miles). For stars this is a convenient unit, but for the Sun, Moon, and planets it is of

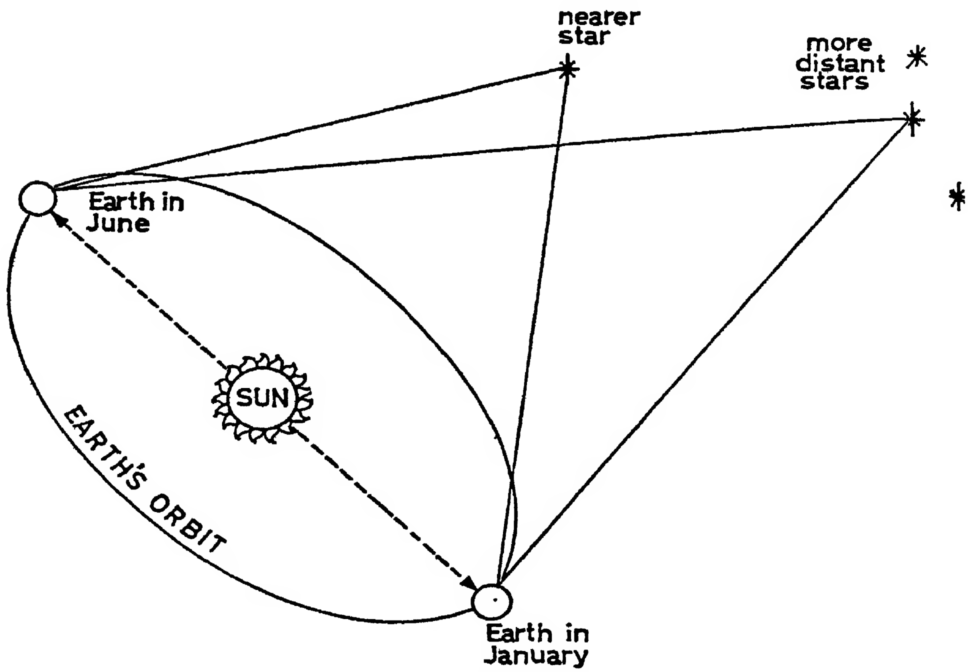
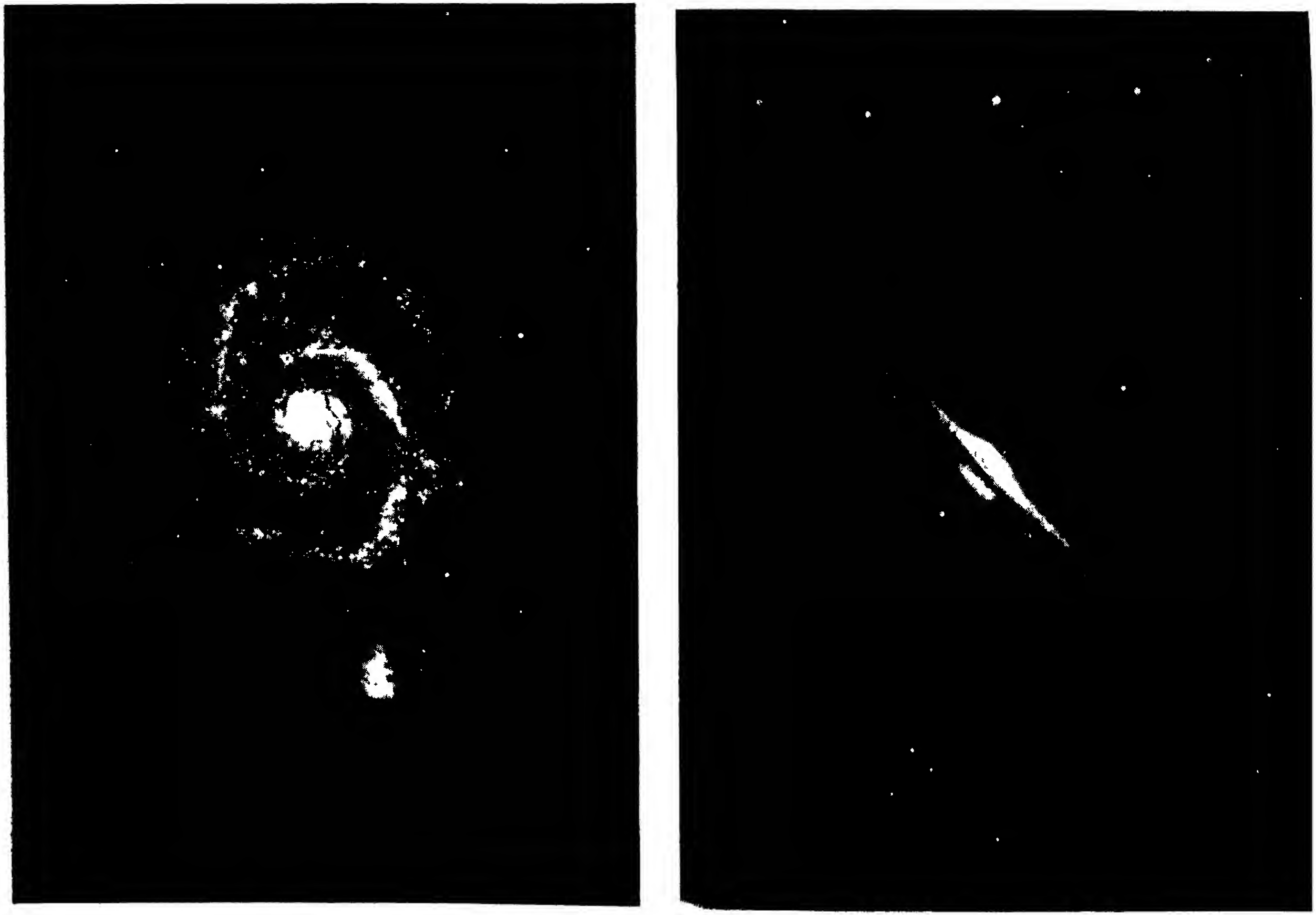


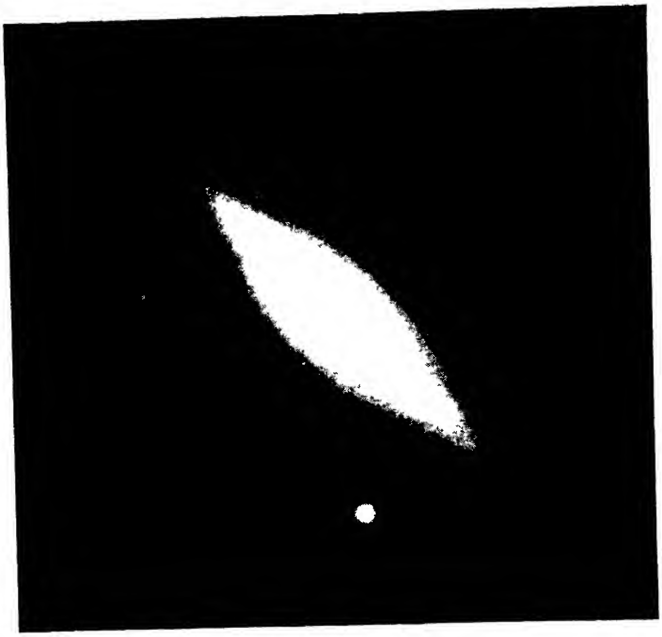
FIG. 12. Star distances.

course far too large. Light takes just over $1\frac{1}{4}$ seconds to reach us from the Moon, and from the Sun a little over eight minutes. So we can speak of the Moon as being $1\frac{1}{4}$ light-seconds away, and the Sun as lying at a distance of eight light-minutes. The fact that the next nearest star to the Sun is almost $4\frac{1}{2}$ light-years away then gives us an idea of how immense stellar distances are.

A more direct way of measuring distances to the Sun, the Moon, and the planets makes use of the fact that radio waves travel at the same speed as light. Using a special radio aerial or radio 'telescope', the astronomer can send out 'pulses' of radio waves. Just like flashes of light, the radio pulses will travel straight out to the



VII (*Left*) The viewer is looking 'down' on a spiral galaxy (M 51) in the constellation *Canes Venatici*, while (*right*) he is seeing a spiral galaxy 'edge-on'. This galaxy (NGC 4565) is in the constellation *Coma Berencies*. Our own galaxy is like these in shape.



VIII *Left*, elliptical galaxy in *Sextans*. *Below*, irregular galaxy: the smaller magellanic cloud.

Moon, the Sun, or planet and then be reflected back. The time for a pulse to go out and return gives twice the distance of the body, and gives it directly in terms of light-seconds (or minutes or hours). So far echoes of this kind have only been sent to the Moon and to Venus and Mars when they have been close to us, but astronomers hope to extend the method to all the other planets in the Solar System.

Applying light-years to the distances measurable by the parallax method described, we find that they will yield satisfactory results for at least 400 light-years—in practice rather more—but even so large a distance as this does not take us very far in space. Indeed it

(a) (b)

FIG. 13. The constellation of the Plough (*a*) as it is now and (*b*) as it will be in 50,000 years.

does not take us very far inside our own Galaxy, the diameter of which is 100,000 light-years; so additional methods of measuring distance must be found if we are to penetrate farther into the universe. Such methods have been found, but they entail examining both the actual motions of the stars themselves and their individual brightness.

It may seem surprising that the stars do actually move about in the sky, for if you look at star maps you will find that the groups or constellations always seem the same. The seven stars of the Plough (Fig. 13(*a*)) still have the same pattern as they did fifty years ago—or five hundred years ago, for that matter. It is no wonder, then, that for thousands of years astronomers thought of the stars as fixed in space. Indeed, it is not 250 years since it was discovered that the stars do in fact all have motions of their own. The discovery was made by Edmond Halley, who is most frequently remembered as the first man to predict the return of a comet. In 1710 Halley had prepared for publication an edition of Ptolemy's star catalogue. This had led him to find differences in the positions of stars as given by Ptolemy and those measured in

his own day. The differences were too great to be accounted for by supposing Ptolemy had made mistakes, and Halley puzzled over them. In 1718 he found the answer—the stars cannot be fixed and must actually move in space. Since 1718 star 'proper motions', as these movements are called, have been measured for many stars. Proper motions appear very small to us because the stars are so far away; Fig. 13(*b*) shows how the Plough will appear in 50,000 years from now, and even at so remote a date the difference is not as much as we might expect. Yet the actual velocities of the stars are very great, and our Sun, for instance, is rushing through space at just over twelve miles per second, so giving us a different viewpoint from year to year.

The fact that the Sun is moving through space at twelve miles per second means that it travels a distance of about 380 million miles every year. Since our Earth is carried along with the Sun, this motion provides us with a second base-line that is about four times the diameter of the Earth's orbit. For stars lying at the sides of the Sun's path, the Sun's motion can be used for finding parallax. The more years that elapse between observations, the longer the base-line and so the farther the parallax measures can take us; this is the reason why distance determinations of this kind are called 'secular parallaxes', from the Latin word *saeculum*, meaning duration.

When the proper motions of different stars are found these will not indicate their movement in space exactly because we are observing from a moving Earth. We are orbiting round the Sun and the Sun is itself moving in space, so these movements of ours must be subtracted from the proper motions if we are to find how the other stars are really moving. The result we obtain is known as the star's 'peculiar motion', and this also can be used to measure distance.

However, we cannot use a star's peculiar motion by itself as a direct measure of distance. This is because we do not know whether the peculiar motion of any particular star is large or small—it may be either. All we can do is to say that if we select a group of stars that we think may all be at the same distance, then there are likely to be as many with large peculiar motions as small and as many in one direction as another. What is more, this likelihood will be increased if we select our stars from all over the sky.

But the problem is, how are we to select stars that are all at the same distance when we do not know their distances? The method astronomers use is to pick stars that both look as bright as one another and also have the same colour. This they do because studies of the way stars shine have shown them that they will more probably be right than wrong.

Once the stars have been selected, their peculiar motions are added together. Because there are as many in one direction as another and as many large as small, they should cancel each other out. In consequence, any motion that remains must be an effect due to the Sun's motion in space, and so the average parallax of the group of stars can be calculated. This average or 'statistical parallax' gives only a general idea of distance: it is unlikely to be correct for any individual star but will give a fairly good idea for the selected stars as a whole. Statistical parallaxes are of great use to astronomers when they want to find out how stars of different kinds are distributed in space.

Another method of distance measurement has been developed for use with double stars. Ever since William Herschel's discovery that some stars are found in pairs, such 'binary systems' have been studied very closely. And although astronomers know that the two members of a binary system are really orbiting around each other, they make their observations by considering one of them as fixed and the other as moving round it. Fig. 14 shows the kind of result that they obtain—in this case for the very bright star Sirius and its companion. The size of the orbit of one star around another will depend upon how massive they both are—the more massive the closer they will be, and also the quicker will each orbit be completed. By measuring the size of an orbit and the period of rotation, and knowing also the masses of the stars, it is possible to work out how big the orbit really is. Knowing how big it is and how big it seems to be in the sky, the distance of the pair of stars can be found. This measurement, since it depends on the motions of the stars, is called the 'dynamical parallax'.

All these measurements—secular, statistical and dynamical parallaxes—have extended our knowledge of distances further and further outwards into space. Yet none of them can take us out into space beyond our own Galaxy. To do this we must find some other way, and this involves knowledge of star brightnesses. As far back

as 150 B.C. the Greek astronomer Hipparchus catalogued the stars he could see, and divided them into six magnitudes, or degrees of brightness. These magnitudes are still the basis of the system in use today, but now astronomers recognize many more magnitudes than Hipparchus ever used. To Hipparchus the brightest stars were magnitude 1, those dimmer were magnitude 2, and so on.

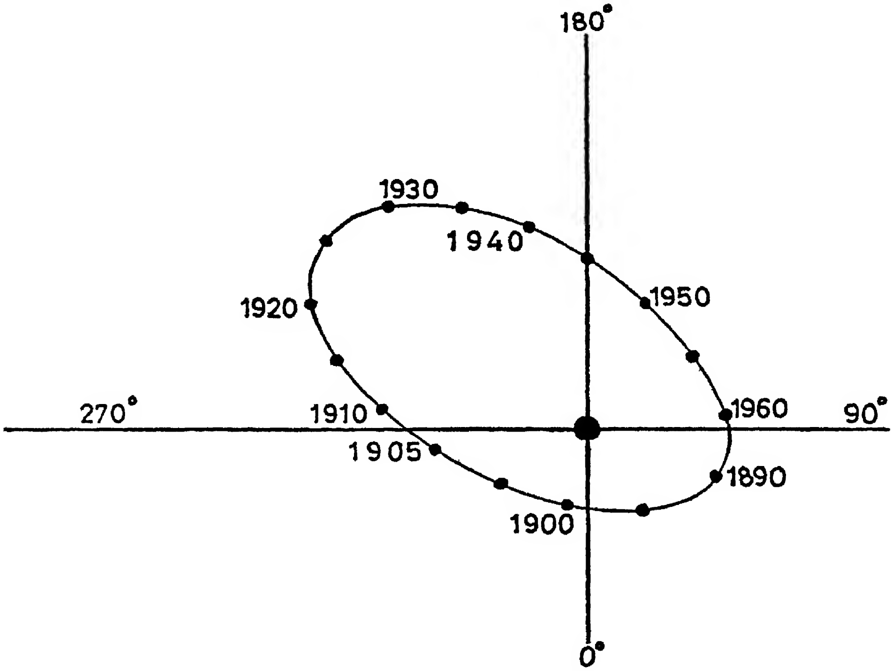


FIG. 14. Orbit of double star.

Today magnitudes are more precisely determined, and stars of magnitude 2 are defined as $2\frac{1}{2}$ times dimmer than those of magnitude 1, magnitude 3 stars as $2\frac{1}{2}$ times dimmer than magnitude 2, and so on. It has been found that some stars are brighter than magnitude 1, and so that the scale of brightnesses can include them the figures have been extended to 0 and below; in consequence a magnitude of -1 denotes a star that is $2\frac{1}{2}$ times brighter than one of magnitude 0 and $2\frac{1}{2} \times 2\frac{1}{2}$ times brighter than magnitude 1. Thus the very bright star Sirius has a magnitude of $-1{\cdot}58$, the bright star Canopus is $-0{\cdot}86$, while Vega—the brightest star of the constellation Lyra—has a magnitude of almost 0 and Aldebaran,

the bright star in Taurus (the Bull), one of 1·06. Astronomers have adopted the value of $2\frac{1}{2}$ for the difference in brightness between one magnitude and the next because it fits in best with the brightness scale that is noticed by the human eye. However, this fact does not prevent the scale from being extended to stars too dim for the eye to see, and a large telescope like the 200-inch at Mount Palomar can photograph stars down to magnitude 23, that is, stars that are 1,500 million times dimmer than Vega!

Astronomers can measure magnitude of stars in many ways. The simplest is to compare by eye the brightness of a star with that of another of known magnitude. This is practised by many amateur astronomers and, with experience, measurements correct to one tenth of a magnitude can be achieved. For greater accuracy we must have more elaborate methods, and this means using some form of light-intensity measurer, or 'photometer'. The form of the photometer will depend upon whether the measurements are to be made directly at the eyepiece end of the telescope or whether they are to be made on photographs of star fields. The first accurate magnitude measurements were made with a 'comparison image' photometer on the telescope. In an instrument of this type (Fig. 15), the star being observed is compared with an artificial star. The brightness of the artificial star (the electric lamp E) is altered by moving the 'neutral wedge' W, which is a piece of glass more darkly tinted at one end than at the other. The observer adjusts the brightness of the artificial star until it is equal to that of the star being observed, and notes the position of the neutral wedge: he compares his result with the position of the wedge for a star of known magnitude, and so obtains a magnitude reading.

The trouble with a visual photometer of this kind is that the artificial star often looks very different from the star being observed, and so instruments have been made to compare a star with an image of a real comparison star, the brightness of whose image can be varied. This gives an improvement, but the readings obtained are still affected by the observer's own eyesight: he still has to judge when the comparison is as bright as the star he is studying. One way of overcoming this is to use a photo-electric cell ('electric eye') at the telescope eyepiece. In this case the light falls on the cell and causes it to emit a small electric current. The amount of the current depends on the brightness of the star. This

can be a very useful method for brighter stars, and is being increasingly used by astronomers, since the brightness of a star can be obtained quite quickly. The next widely used way of measuring stellar magnitude is photography. This is possible

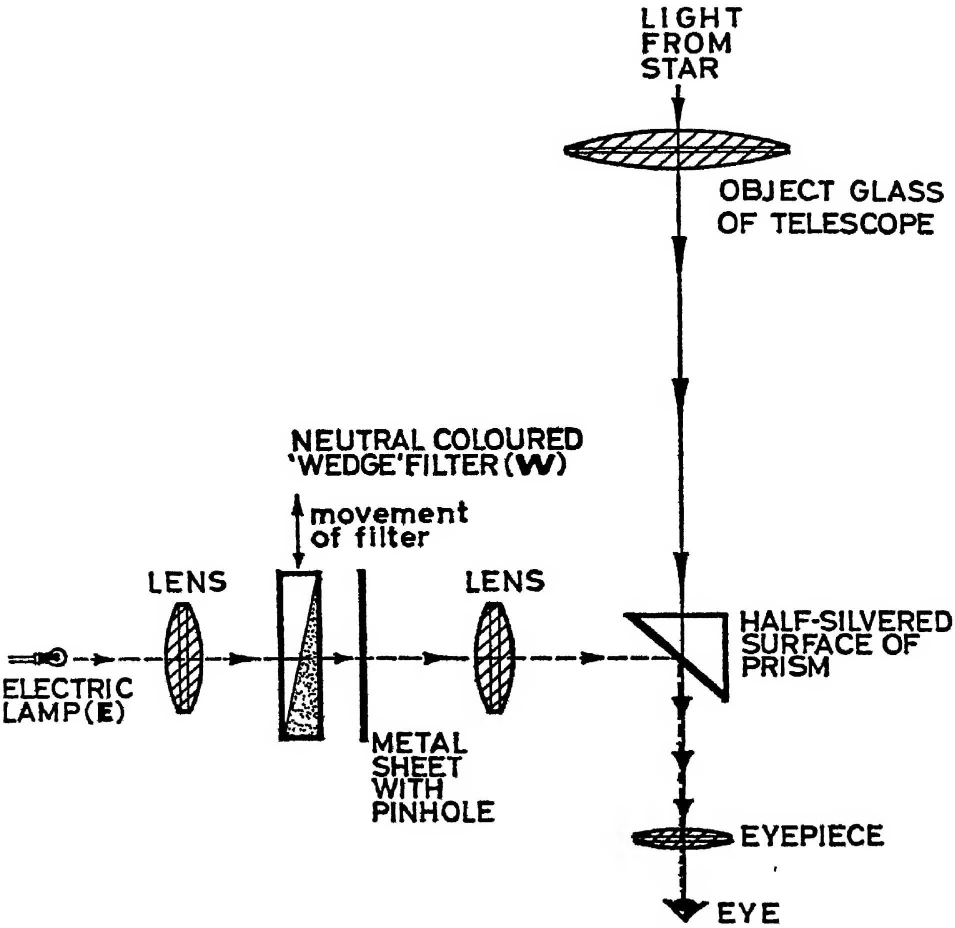


FIG. 15. Artificial star comparison photometer.

because the brighter the star, the larger and denser appears its image on a photograph. So if the sizes of the star images are measured, astronomers can find the brightness of the stars.

The measurement of the images is carried out by a 'micro-photometer'. In the most usual instrument of this kind, there is a microscope in which a photo-electric cell takes the place of an

eyepiece. The photographic plate that has been exposed in the telescope is placed in a holder under the microscope and the images of the different stars are measured. This is a skilled task and it takes some time to measure all the stars on a plate, so that a new kind of microphotometer is coming more and more into use. It is an electronic microphotometer, and a picture of it is on Pl. VIA. At the top is a lamp-house that feeds light in two directions; one leads directly to a photo-electric cell and the other to a microscope lens underneath. The photographic plate is placed just under this microscope lens and, after the light has passed through it, a picture of the plate is thrown on the screen at the front of the instrument and also goes to a second photo-electric cell. Only part of the plate can be seen at once, but it can be moved about by remote control so that every star is in due course shown on the screen. A star is lined up on the cross-lines and a mask is adjusted so that it just touches the edges of the star image. Controls are altered until the little 'tuning indicator' just below the screen shows that the light through the mask to one photo-cell is equal to that going direct to the other cell. The magnitude of the star is then given. The instrument is easy to use and gives answers correct to one hundredth of a magnitude.

To obtain the distances of stars from their magnitude measures, astronomers can use all kinds of stars, provided their light is analysed, in a way that we shall come to later (*see* p. 42). However, there are some special kinds of star that can be used without such analysis. These are variable stars, which keep changing the amount of light that they emit. There are many stars of this kind, but the most useful for distance measurements are the Cepheid variables, so named because the first star of this kind to be discovered was one in the constellation of Cepheus.

The importance of the Cepheid variables lies in the fact that the time they take to vary depends upon the brightness of the star. For example, the star Delta (δ) Cephei varies its light as shown in Fig. 16 and so its period of variation is seen to be about $5\frac{1}{2}$ days. Now Fig. 17 shows how the brightness is related to the period of variation, and from this we can see that δ Cephei must have a true brightness ('absolute magnitude') of $-1{\cdot}4$. But from our observations we find that at best it has an apparent brightness of only $3{\cdot}7$, or one hundred times less. Now the absolute magnitude of a star

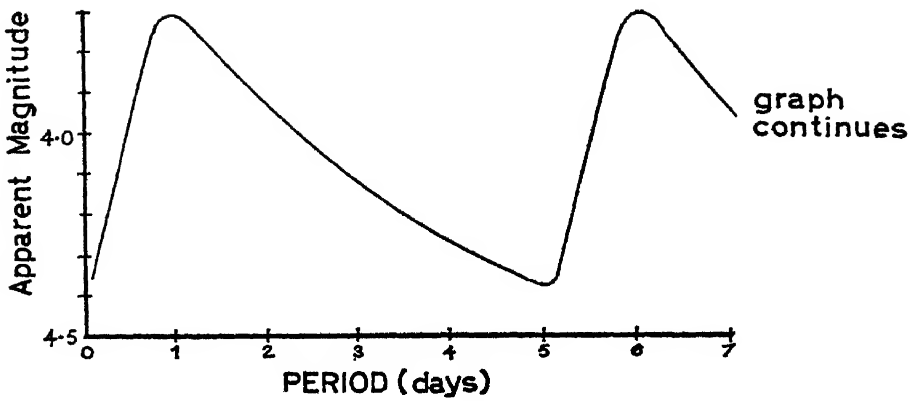


FIG. 16. Light curve of Delta (δ) Cephei.

is that magnitude it would have if it were 10 parsecs or 32½ light-years away, and knowing how brightness diminishes with distance, astronomers can work out how far away δ Cephei must be if it is to appear with a magnitude of 3·7. The answer comes out to a little more than 100 parsecs or approaching 330 light-years.

Some other stars, known as RR Lyrae variables, are also of this

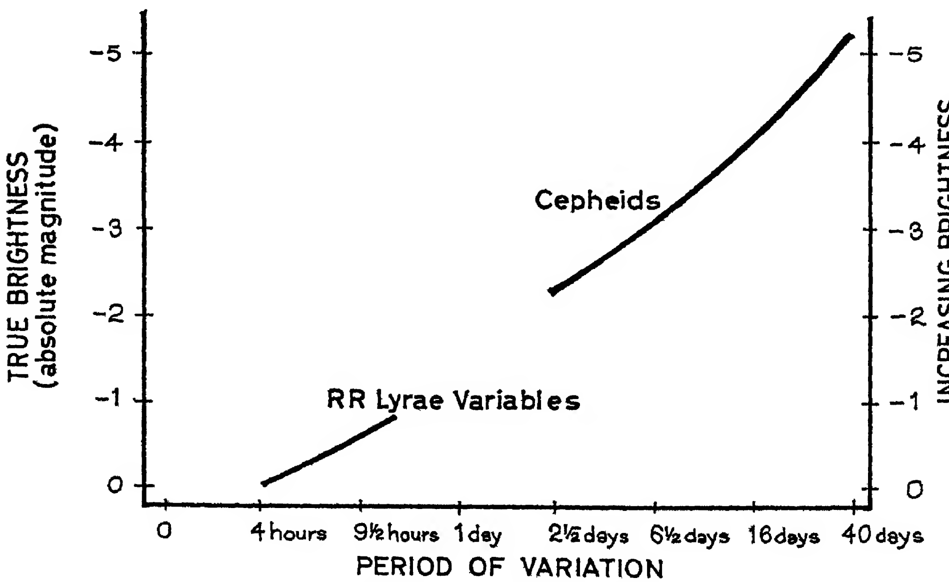
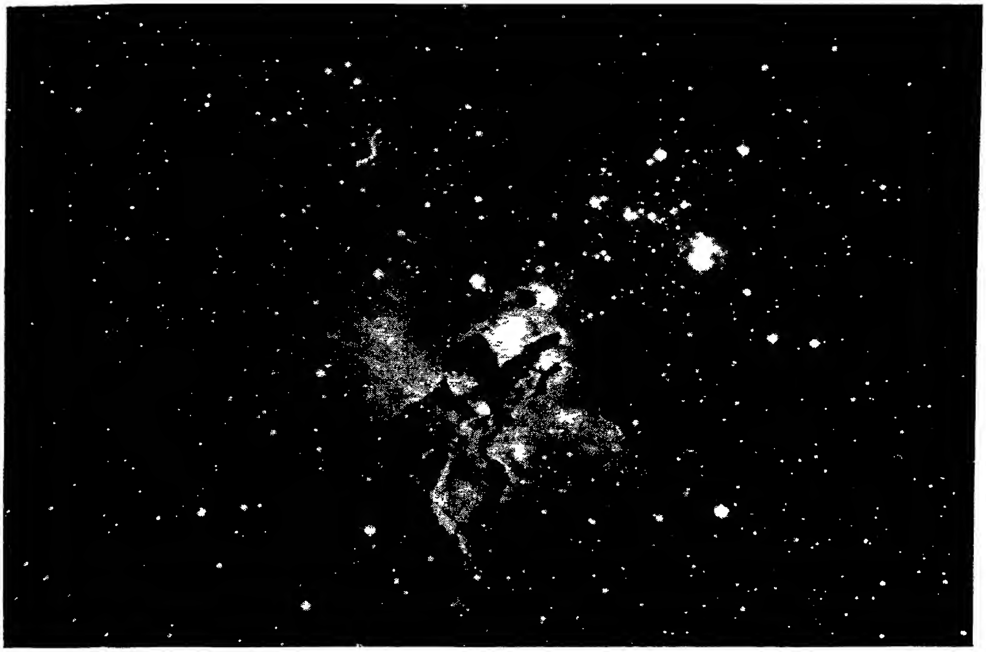
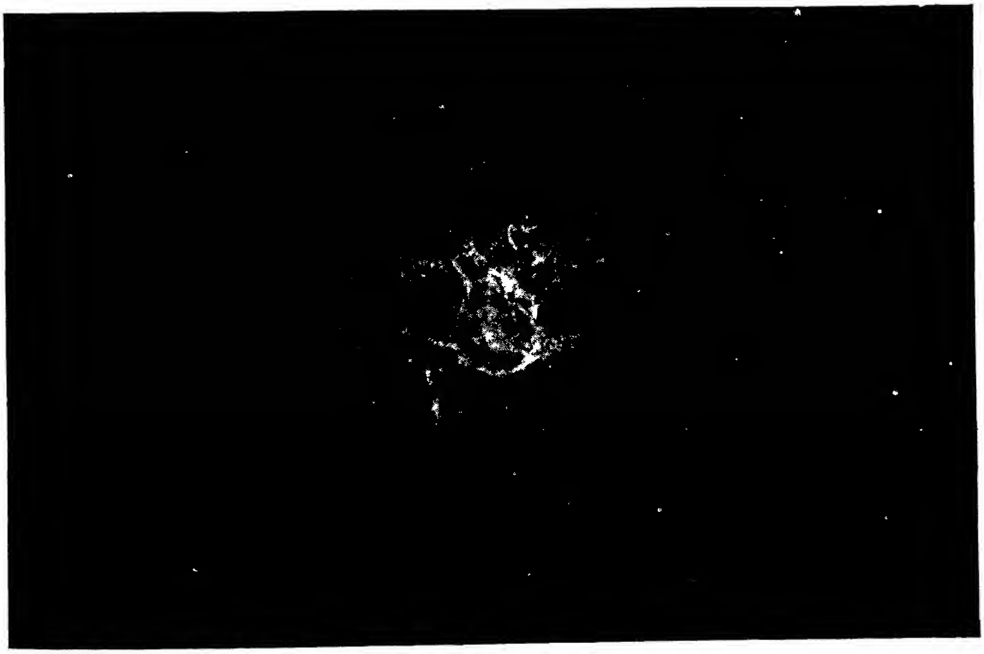


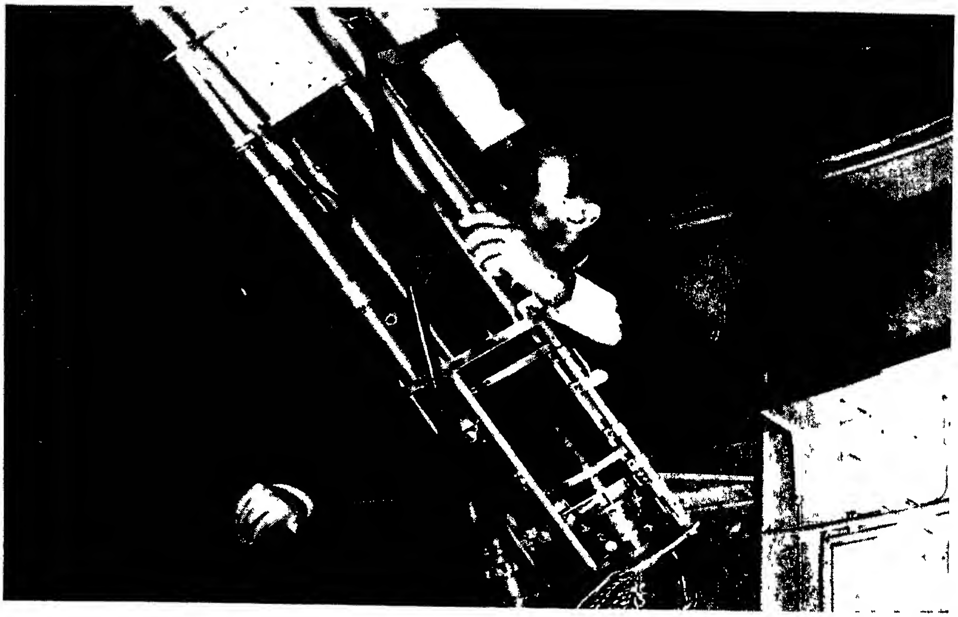
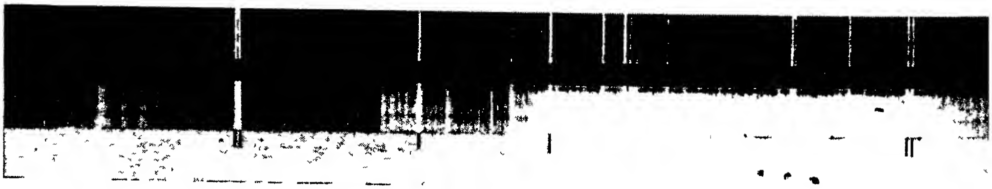
FIG. 17. Period and luminosity relationships for Cepheid and RR Lyrae variables.



IX There is much dust and gas within our own galaxy (*above*). This photograph is of a section of the Milky Way. The difference between the nature of the stars and of gas can be determined by a photograph of a spectrum checked against comparison spectra (see Pl. X, foot). *Below*, the 'Crab' nebula is an expanding shell of gas, all that remains of the supernova explosion in A.D. 1054 in the constellation of Cancer.

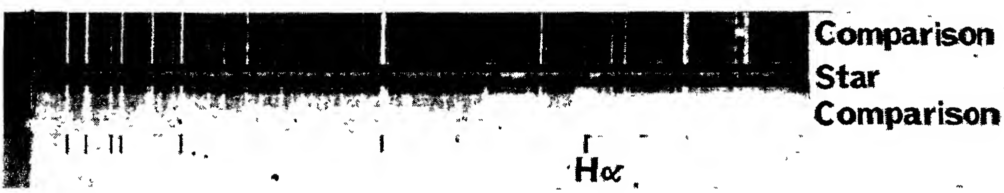


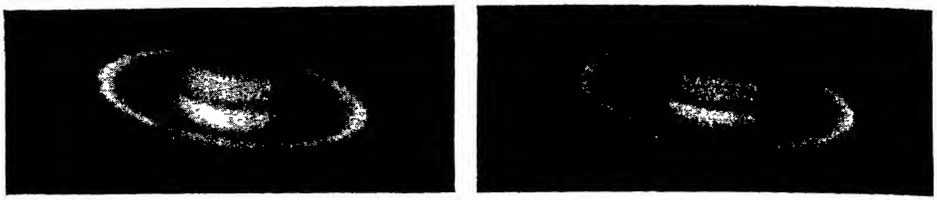


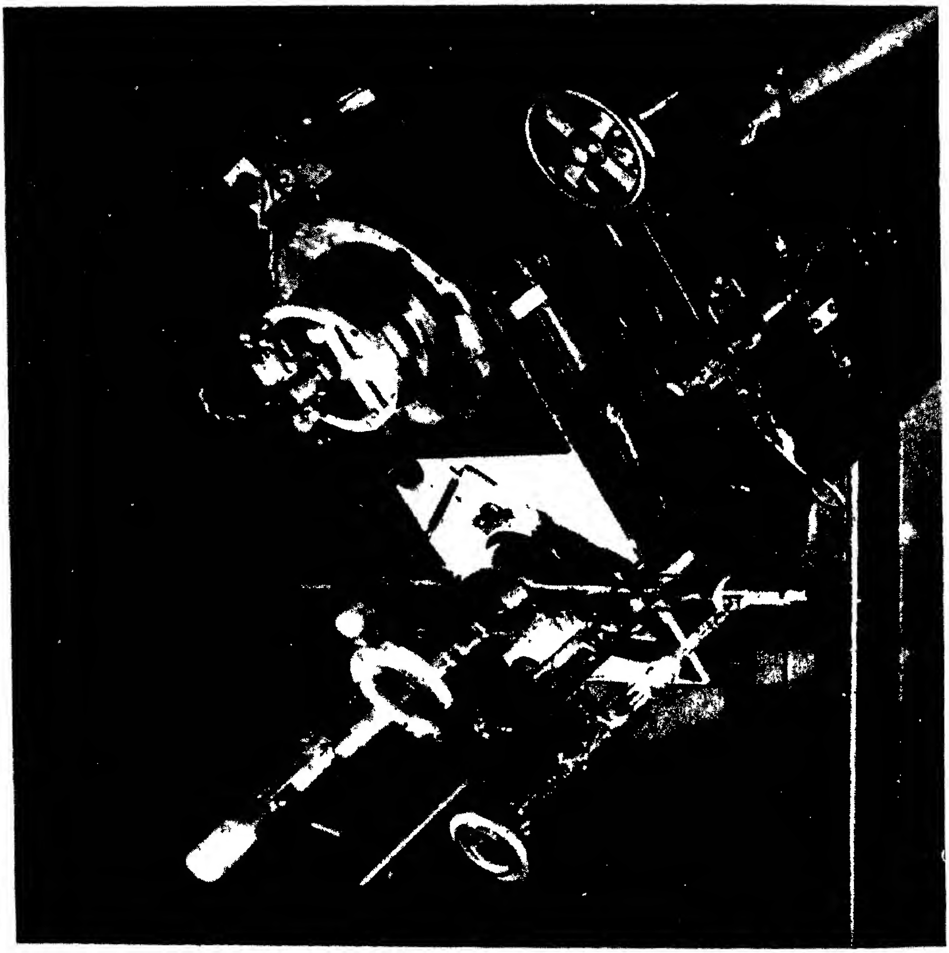
XI *Left*, the lunar crater Maurolycus as displayed on a television screen, using a special television camera fitted to a 12-inch refracting telescope (*opposite*).

X *Opposite, above*, two composite photographs by Dr F. Zwicky of the spiral galaxy M 51. The left-hand picture shows the blue Population I stars, and the right-hand picture the redder Population II. Compare these pictures with Pl. VII (*left*). *Centre*, a special television camera fitted to a 12-inch refracting telescope. *Below*, part of the spectrum of the star Eta Cephei with a comparison spectrum above and below (the star spectrum is the thin strip in the centre). The photograph was taken by Professor Roy Garstang, using a large fixed spectroscope with the 82-inch reflector at McDonald Observatory University of Texas. The spectrum shows dark lines due to the absorption by the star's outer gases. The lines indicated are due to the metal iron, and the strong dark line marked Hα to the right (red end of the spectrum) is caused by hydrogen. The comparison spectra show bright lines from iron vaporized in an electric arc. There is a shift to the left (blue end of spectrum) showing that the star is moving towards us: the amount of shift indicates a speed of 55 miles per second.





XII *Above,* two photographs of Saturn taken by Wlerick and Rösch, using an electron camera of the kind designed by Professor Lallemand (*below*) and fitted to a 12-inch refractor.



kind, but their periods of variation are very short, ranging from a few hours to about 1½ days, compared with the 2½ days to over a month for the Cepheids. The RR Lyrae variables have their true brightness and periods linked together by a similar (although different) relationship to the Cepheids. They can be used for determining distance too.

By using Cepheid and RR Lyrae variables, the astronomer can gauge distances far outside our own Galaxy. Such stars can be observed in the nearer galaxies in space, and so we can say that they take our distance measurements out to many millions of light-years. To go further still, measurements of the brightness of spiral and other galaxies (Pl. VIII) can be made to yield a reasonably good idea of distance, because astronomers can assume that most galaxies of a particular kind are pretty well the same in brightness. In this way, telescopes have probed at least six thousand million light-years into space. Of course, such measurements are not absolutely certain, and must be checked in other ways, as we shall see.

IV. *Analysing Starlight*

It is always dangerous to say what can never be known—at least as far as scientific discovery is concerned. In 1755 the philosopher Immanuel Kant put forward the idea that the nebulae were separate systems of stars, each one having condensed from a cloud of gas. It was a good idea, but another philosopher, Auguste Comte, criticized it because, he claimed, it was a theory that no one could prove. We could never know what the stars were made of for the simple reason that we could never get to them and bring back pieces to examine in the laboratory. But Auguste Comte was

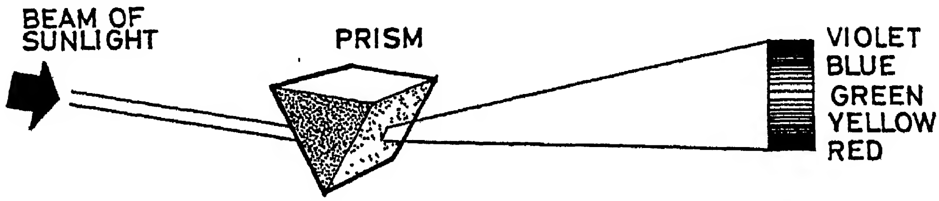


Fig. 18. Prism and the spectrum of colours.

wrong. Admittedly, we have not sent space probes to the stars, but it is pointless to do so: they would be vaporized before they had come within a thousand miles of a star's surface gases. Yet we do not have to bring back samples of a star to discover what it is made of. We can do this much more simply, merely by analysing the light that it sends out. And this Comte never imagined.

When sunlight passes through a prism it is dispersed into its various colours. At one end of the coloured band, or 'spectrum', is deep red and at the other a deep violet. In between are the other colours of the rainbow with which we are all familiar (Fig. 18). You can see a spectrum if you look at sunlight reflected from the bevelled edge of a mirror, and you will notice that the colours are all very bright. In fact the Sun is shining in every colour at once, and what we call 'white' is merely the mixture of all these colours together.

The first astronomical interest in the spectrum arose in 1802, when William Wollaston examined the Sun's spectrum very carefully in an instrument that he had designed. Wishing if possible to separate the colours, Wollaston first passed the sunlight through a narrow slit before letting it reach the prism and be dispersed. When he examined the spectrum with a small telescope he did not find any separation between one colour and another, but instead he discovered that the spectrum was crossed by a multitude of very thin black lines. What these lines were he did not know—indeed it was not until fifty years later that the mystery was

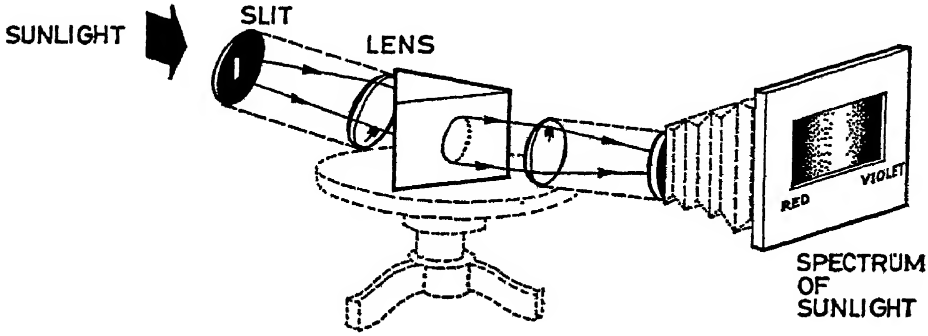


FIG. 19. Spectroscope and solar spectrum.

solved—but their discovery stimulated a lot of interest. Joseph Fraunhofer in Germany was particularly intrigued by them, and set about observing them through what was called a 'spectroscope' (Fig. 19), and he mapped the positions of as many as he could see. Fraunhofer also discovered lines in the spectrum of every planet and noted that the stars themselves provided spectra.

It was in the physics laboratory that the answers were found to the host of questions that astronomers were asking. After many experiments, two German physicists, Gustav Kirchoff and Robert von Bunsen, using a spectroscope, discovered that all kinds of substances, if heated until they glowed, each had its own kind of spectrum. For instance, glowing gas given off by the heated metal sodium showed a spectrum that was completely black except for two bright yellow lines. Glowing hydrogen gas gave a black spectrum with a series of bright lines ranging from red through to violet. In fact every gas made of a single chemical element possessed its own pattern of bright lines. As a result, we can look on

the spectrum lines as the 'finger-prints' of the different chemical elements.

Yet this was not all. Kirchoff and Bunsen also found that, if they heated a solid until it glowed, they then observed a continuous spectrum—at least, the spectrum looked continuous, but it was really made up of thousands and thousands of shining lines of every colour, each so close to the next that the effect was that of a continuous coloured band. But what of the dark lines that had been the cause of all the inquiries in the first place? How could they be explained?

The answer to the dark lines was found by having two glowing sources—a bright light, say, and sodium vapour. The bright light used in Bunsen and Kirchoff's day was a block of lime heated until it glowed, but any incandescent solid will do and a really bright electric light is quite satisfactory. At any rate the bright light gives a continuous spectrum, and by itself the sodium will give a pair of yellow lines (Fig. 20(a)). But when the sodium is placed in between the bright light and the slit of the spectroscope, the sodium lines appear dark against the background of the bright continuous spectrum (Fig. 20(b)). The sodium vapour is cooler than the bright light, or rather the wire filament inside it, and so it absorbs energy from the light. The energy it can absorb leaves its finger-print in the same way as does the energy that it emits, so instead of two bright yellow lines we get two dark lines across the yellow part of the continuous spectrum.

If we now look at the spectrum of the Sun through a spectroscope with a slit, we shall see that it gives the astronomer evidence of cooler gases lying above the part that gives out the continuous spectrum. The positions of these lines allow the astronomer to identify all the chemical elements that cause them and so discover what substances are present in the Sun. What is more, the Sun is no more than an ordinary star, and if a study of its spectrum provides evidence of the chemicals in it, then a study of the spectra of other stars should give astronomers evidence of the chemicals in them—at least, so argued the Italian priest Father Secchi and the English astronomer William Huggins. In 1862 both began to use spectroscopes on the stars, Secchi to make general surveys of the sky, and Huggins to make precise measurements of lines with a view to finding out what substances were making them.

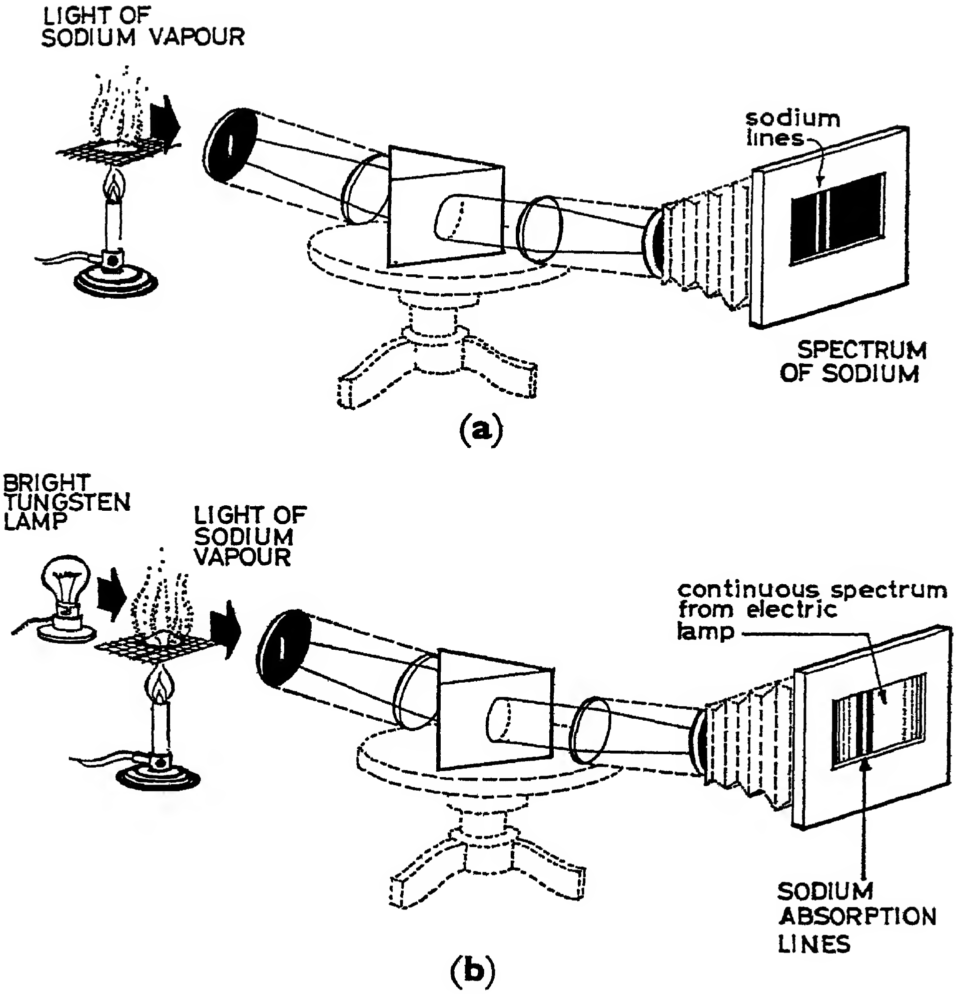


FIG. 20. Bright line and dark line spectra.

Since then the spectroscope has developed into one of the astronomer's most powerful tools and, by examining the lines in detail, not only the chemicals present, but also the temperature, the pressure of the gases, and the electrical and magnetic fields of a star can be found. So it has turned out that Auguste Comte was wrong to a surprising degree!

From observations with spectrographs (spectroscopes with built-in cameras) and the studies of atomic physicists, we can now

piece together a general picture of the different kinds of stars that exist, and go a long way to solving a problem that has puzzled astronomers for generations—the question of how the stars shine.

It will be best to deal with these in order, and begin with the various kinds of stars that astronomers recognize. These can be divided into seven main types, with an additional four types for certain special stars; but it is only the main types that need concern us. Secchi recognized four types and other astronomers split them into more and designated each by a letter of the alphabet, but since then astronomers have kept revising them, so that now the letters used seem rather a strange mixture. They are, in order, O.B.A.F.G.K.M., and are usually memorized by the jingle, 'Oh, be a fine girl, kiss me'! Yet however disconnected the letters may seem, the scheme that they represent is straightforward enough. O-type stars are those which are very bright at the violet and blue end of the spectrum and show lines that indicate that much hydrogen and helium gas are present. Such stars are very hot indeed, having a temperature of about 36,600° C., or more than six times that of our own Sun. The B-type stars are a little cooler and shine most brightly in the blue part of the spectrum. Very strong in hydrogen, these stars have a temperature of some 28,000° C., and the middle star of Orion's 'belt' is typical of this kind. As we continue down the list, the stars become progressively cooler. A-type stars are white and very strong in hydrogen, with temperatures in the 10,000° to 7,500° C. range. F-type are cooler still and spectral lines due to metals show up very strongly. Sirius is an A-type star and Canopus a typical F-type. Our Sun is a G-type star. The lines due to vapours of metals are strong and its temperature is around 6,000° C. Yet although we think of sunlight as white light, the Sun is a yellowish star compared with A- and B-types, and it is in the yellow part of the spectrum that it shines most strongly. In K-type stars the temperature is still lower—around 4,000° C.—while the M-type stars are red in colour with a temperature a thousand degrees lower than those of K-type.

The difference between one type of star and another is found by examining their spectra, and the different types provide a good guide to star temperatures. Now, as it turns out, this is very helpful as a measure of distance because the temperature of a star

gives a strong indication of its actual brightness. For instance, O-type stars are all extraordinarily bright radiators of light as well as being strong radiators of heat and, on the average, are 36,000 times as bright as the Sun. B-stars are also very bright and typical ones are found to be some 10,000 times brighter than the Sun, but as we go down the scale the brightness decreases. K-type

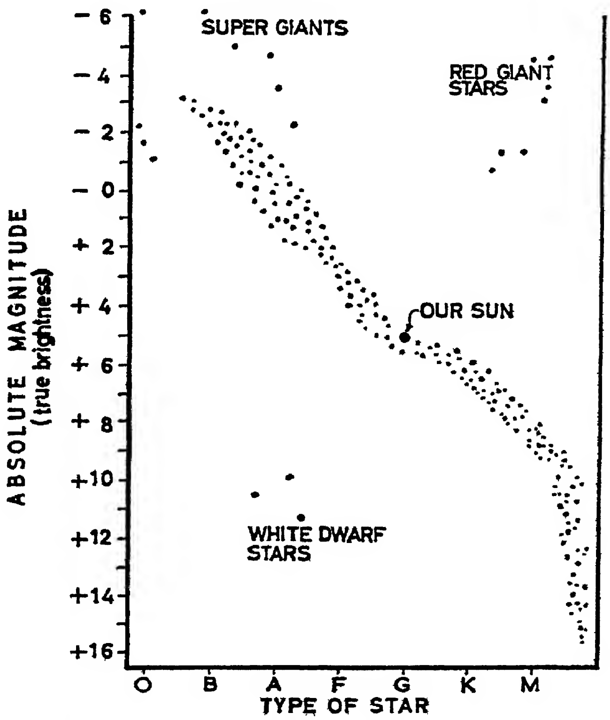


FIG. 21. Relationship between spectra of stars and their true brightness.

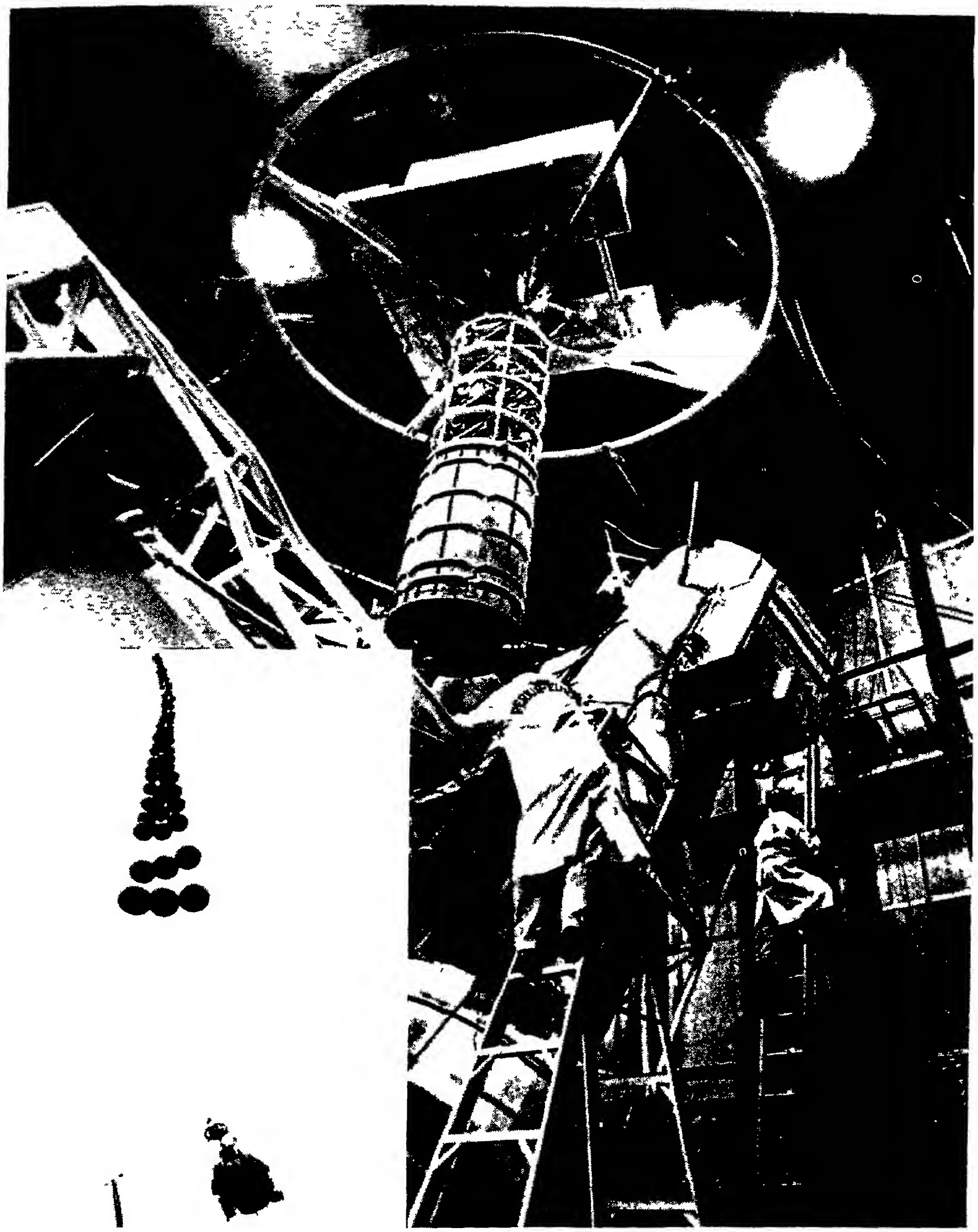
stars are some six times dimmer than the Sun as well as being cooler, and M-stars are, on the average, a hundred times dimmer (Fig. 21).

So it becomes clear that if we can obtain the spectrum of a star and so determine its type, then we shall have some idea of its true brightness. On the other hand, if we can observe a star at all, we can find its apparent brightness. Thus by combining the two—the real brightness derived from spectral type, and the observed apparent brightness—we can gauge the star's distance. At least

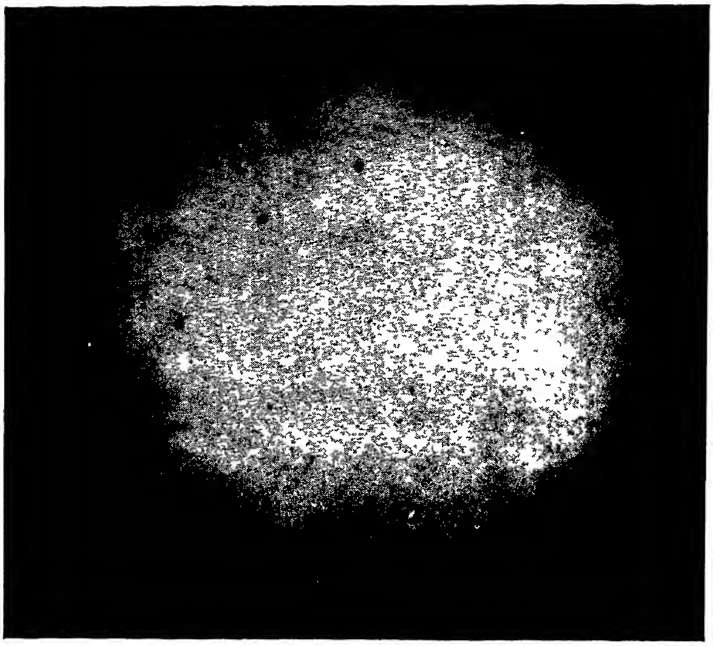
this is the principle, although it is not quite so simple as this in practice. Some stars, notably the red M-type, are to be found with a giant emission of light. Such 'giants' and 'supergiants' (as the immensely bright ones are called) will clearly give an incorrect distance determination. Again, there are 'dwarf' stars that are much dimmer than the average A- or B-type stars, and these too will falsify our results. But astronomers are on their guard against these exceptions, and also against the fact that the space between the stars is not completely empty, and may in consequence cause some dimming of a star's light on its way to us. With these provisos in mind, the spectroscope can be a very helpful guide in determining distance, and so 'spectroscopic parallaxes' are much used.

The star spectra so far mentioned all show dark lines against a bright continuous background. The lines, as we have found, are due to the presence of cooler gas lying above the main radiating mass of the star. But what of the main part of the star itself? Why does it give a continuous spectrum? In the laboratory Kirchoff discovered that solid bodies gave a continuous spectrum; does the continuous spectrum of a star, then, mean that most of it is solid? The answers to these questions can be found if we turn once more to Kirchoff and Bunsen's experiments.

Kirchoff and Bunsen showed that a substance that emitted light only in certain parts of the spectrum—sodium vapour, say, that emits only yellow light—can absorb light only in exactly the same part of the spectrum. In other words, because sodium vapour emits only yellow light, it can absorb only yellow light. And so it is with all substances. They can emit in only those parts of the spectrum in which they absorb radiation. In a star we observe dark absorption lines because the star is surrounded by cooler gases that absorb some of the light from the main part of the star itself. Deeper down, below these surroundings, the star is hotter and its gaseous material is far more closely packed together. It is still a gas, but it is so closely packed that we could not shine sunlight or any other light through it. In fact the gas is under such pressure that the main body of a star is opaque and we cannot see through it at all. So although a star is made of gas, a star's main body will absorb light from every part of the spectrum. This means, then, that in its turn it will emit light in every part of the



XIII At the foot (*inset*) is a photograph of the gondola in which Dr Dollfus has travelled ten miles up, using gas-filled balloons to lift him and his equipment. The other picture shows Professor Schwarzschild's radio-controlled Stratoscope balloon equipment being prepared: the large reflecting telescope is seen in the middle.



XIV *Above*, the Sun in extreme ultra-violet light photographed from a United States rocket at a height of 123 miles. *Below*, an Aerobee-Hi rocket photograph of the Sun's X-ray radiation.

spectrum. In this way the star behaves just like a solid, absorbing light from every part of the spectrum and emitting light in the whole range of spectral colours. In consequence, each gives us a continuous spectrum.

The amount of gas in a star is prodigious. In the Sun, for example, the quantity of gas is more than 333,000 times that of all the material in the Earth—and the Sun, we must remember, is not a large star. A star holds together because of the gravity of its material pulling it all together into a globe-shaped body. Towards the centre the material is extraordinarily closely packed due to the mass of material lying above it. Yet even so it is still a gas and the whole thing would collapse in on itself were it not for what happens in the centre, for it is here that processes occur that cause a star to shine.

In the central regions of a star the atoms become so closely packed together that their structure is broken down. Whereas we can think of atoms ordinarily having a centre, or 'nucleus', around which electrons are for ever orbiting, in a star's centre this structure no longer exists. The atomic nuclei are piled together and their bonds with their electrons are broken. In fact we can picture it almost as a core of atomic nuclei surrounded by a cloud of electrons. But this is not all. The pressure is such that the atomic nuclei are themselves broken down and, in consequence, nuclear reactions take place. In fact the whole of the central parts of a star are rather like the inside of millions of exploding hydrogen bombs. It is here that a star's energy is generated and the radiation starts on its journey out into space. However, as we have seen, a star is opaque to radiation, so that the energy has to be used in other ways. Some heats the gas lying above it, and so the radiation moves outwards by being transferred from one atom to another. Some is used to counteract gravity and push on the material that lies above, in this way preventing the star from collapsing in on itself.

In most stars a state of equilibrium is reached. The outward pressure of radiation equals the inward pull of gravity, and the remaining energy is transferred outwards by the gas atoms until it is at the 'surface' and is free to radiate away into space (Fig. 22). All the same, there are some stars where things do not quite work out in this way. In a few, not all the energy is used, and some of the

energy builds up until it escapes by blowing a great layer of gas right away from the star in all directions. When such an explosion occurs, the star temporarily becomes very bright and it may well be seen by the eye instead of being visible only in a telescope. It looks for all the world as if a new star has suddenly appeared, and it is for this reason that such stars are called 'novae' (new). On rare occasions the release of energy is so immense and the explosion so catastrophic that the star is virtually blown to pieces. Little

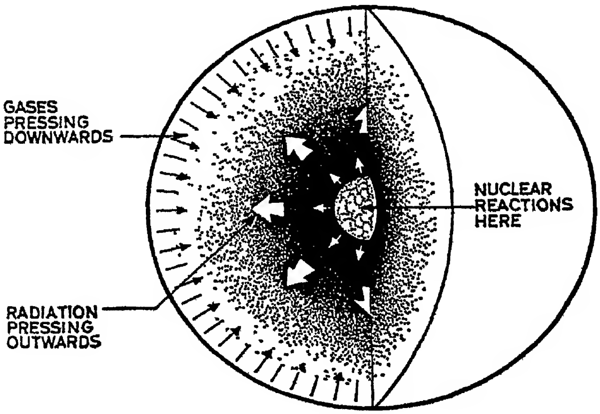


FIG. 22. How a star keeps its shape.

remains and its radiation is short-lived, but while it lasts such a 'supernova', as it is called, may shine with a brightness 200 million times that of the Sun.

After a nova or supernova has exploded an expanding shell of gas spreads outwards into space. Astronomers know that it is spreading even though the distance prevents them from seeing any actual change in the shape of the gas shell. The clue is given by the spectroscope and a shift in the position of the spectral lines. Such a movement of the lines is usually called a Doppler shift, after the Austrian physicist Christian Doppler, although in fact Doppler never discovered it! What Doppler did, however, was to point out that if a moving source of sound changes with respect to our own position—he gave the instance of the whistle of a railway train—then we should hear a change of pitch. If you have ever stood on a station platform and heard a train rush through the station blowing its whistle, you will be familiar with the effect. As

the train comes towards the station, its whistle has a high pitch, but as it moves away the pitch is lower. In 1842 Doppler accounted for this quite correctly by considering the movement of the sound waves concerned. Their pitch, he knew, depended upon the frequency with which they reached the ear. Now, he argued, when the train is approaching, the waves will follow one another quickly (high pitch), but when the train is moving away they will arrive at the ear less frequently and consequently their pitch will be lower.

Where Doppler went wrong was in his application of this theory to starlight. Light can best be thought of as travelling in waves, although waves of a kind rather different from those of sound; those light waves that are short in length and whose pulses strike the eye at a rapid frequency we see as blue, those long in wave-length and thus of a lower frequency we see as red. So Doppler argued that the stars should appear to change colour as they moved towards or away from us, and believed that he had in this way given the reason why stars are of different colours. Yet this is not so, as the French physicist Hippolyte Fizeau pointed out later, for the light we see is not the entire range of all that a star emits. In consequence if a star is, say, moving away from us then although its light will be altered to a lower frequency it will not appear redder in colour, for the simple reason that while the blue light will appear green and the violet light appear blue, the light beyond the violet end of the spectrum (the ultra-violet) will take the place of the violet and we shall be back where we started. But, as Fizeau also pointed out, although the star would not change its colour, there would be changes in its spectrum. These changes would show up as a shift of the spectral lines: to the red end if the star is moving away from us, or towards the blue end if it is coming nearer. This is because every line is due to light emitted at a particular frequency—the frequency of hydrogen, or sodium, or of whatever chemical element it may be—and if the star is moving then this frequency will be altered.

That this shift of spectral lines does happen is most useful to astronomers, for the motion of a star, or a gas cloud, or even a galaxy towards or away from us is undetectable by any other means. Ordinarily we can observe the approach or recession of something by watching its change in size, but all celestial bodies are too far away for us to be able to see such a change. The shift of

spectral lines is, therefore, a really vital clue. It is only a small shift—hardly possible to detect visually—and almost all observations have been made by using photography, so that the results can be examined under a microscope. Only in this way can minute shifts be detected and, of course, only with photography is it at all possible to detect spectra from really distant objects. To detect the tiny shifts astronomers use a multiple exposure technique. As soon as they have lined up their telescope and focused the star image on the slit of the spectrograph, they take a 'comparison spectrum'. This is a spectrum generated by the light of a

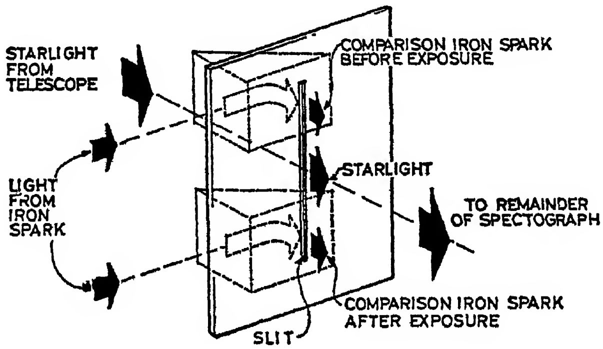


FIG. 23. How a comparison spectrum is obtained.

spark, usually caused by a high-voltage discharge between two iron electrodes. The light of the spark is collected and passed to a reflecting prism fitted to one end of the slit, so that it exposes only a part of the plate (Fig. 23). Next the stellar spectrum is photographed with a long exposure, the starlight falling directly on the centre section of the slit. Finally, after the stellar exposure, a second comparison spectrum is taken, again using the iron spark but this time directing its light through a reflecting prism at the opposite end of the slit. The astronomer ends up, then, with three spectra on a plate all next to each other (Pl. Xc). At the top is a comparison spectrum taken just before the beginning of the exposure, in the middle is the stellar spectrum, and at the bottom is the comparison spectrum taken after the exposure is over. In this way an observer has comparison spectra which will show up any change in the equipment during exposure, and that will also provide a standard from which shifts of lines may be measured.

Spectral shifts show all movement in the line of sight between ourselves and other celestial bodies. The rotation of the Sun can readily be detected, as well as the rotation of the rings of the planet Saturn. The motions of the stars as they orbit round our Galaxy can also be partially found in this way, but the most spectacular results have certainly been those concerned with distant galaxies. Here astronomers find that almost every single one is moving outwards into space. The few exceptions are all members of a 'local' group of some thirteen galaxies that includes our own. Otherwise the universe seems to be expanding outwards, with the more distant galaxies moving faster than those nearer to us. This indeed provides an additional way of measuring distance, for the line-of-sight velocity is proportional to distance and so can be used when all other methods, except perhaps for brightness measurements, have failed.

The analysis of starlight was begun just over a hundred years ago, and since then it has revolutionized astronomy. The spectroscope has brought the astronomer a host of observational facts that he could have found in no other way. It is these that to a great degree have enabled him to piece together his modern picture of the universe. Now still newer optical techniques are beginning to transform this picture even further. To these we must now turn.

V. The Way Ahead

ONE of the many ways in which optical astronomers are forging ahead is in their use of photography. As we have found, photography has made it possible to penetrate into space farther than by the eye, however large the telescope may be. It has also allowed astronomers to measure the positions and brightnesses of stars far more accurately than could be done otherwise. Now astronomers are beginning to make use of the fact that photographs can be taken in such a manner as to select some objects in the sky and to reject others. In this way they can undertake special surveys of stars quickly and easily.

As a simple example: Suppose we want to count the number of red stars, and the number of blue ones, in a given area of the sky. The technique is to take two different photographs, using the same telescope. One is taken through a red filter and the other through a blue. The negative taken through the red filter will show the red stars as large dark blobs because the filter will have transmitted all the red light. On the other hand, the filter will have kept back most of the light from the blue stars and so these will appear as smaller black dots on the negative (Fig. 24(*a*)). Now if we make a positive print on a glass sheet we shall have the red stars as big clear blobs, and the blue stars as small ones. The white stars will be intermediate in size (Fig. 24(*b*)).

The negative taken through the blue filter will show the opposite effect. Blue stars will be big black blobs and red stars will appear as small ones (Fig. 24(*c*)). If the glass positive print taken through the red filter is fixed to the glass negative taken through the blue filter, we shall have a photographic sandwich rather like that shown at (*d*) in the drawing. From this an ordinary print can be made. The result is shown at (*e*), the blue stars being round white blobs, the red stars black blobs with a bright central dot, and the white stars are dark blobs of intermediate size. Each type

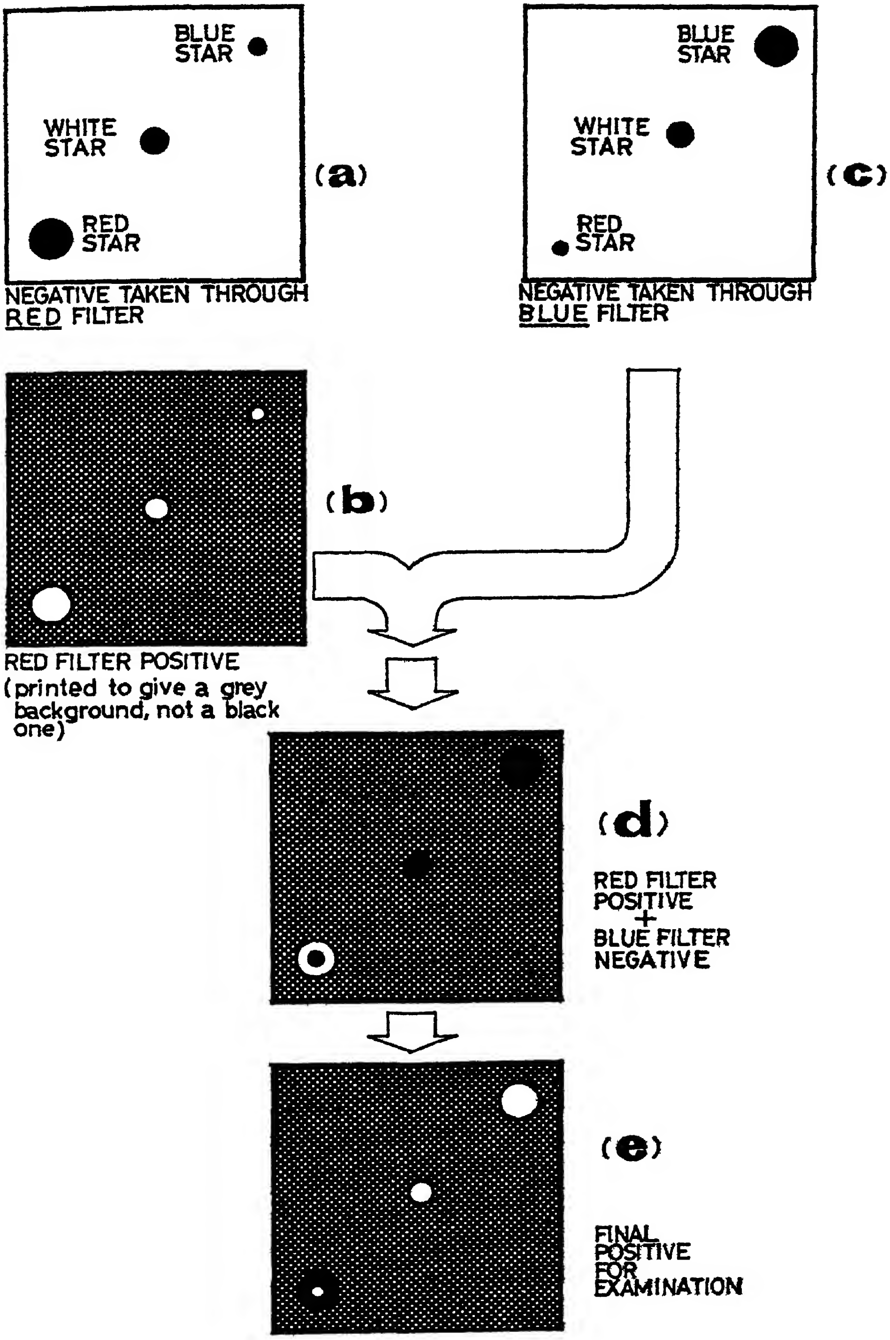


FIG. 24. Star colours and photography.

of star can be readily picked out, and in this way counting them is both easy and quick—it is also far less liable to error. Moreover, using a special new telescope known as a Schmidt (Pl. VIB), which has a mirror and also a 'correcting' lens at the front, astronomers can photograph very big areas of the sky, and the technique can thus be a great time-saver.

This method of using a negative and a positive together to make a print also allows astronomers to see at a glance how, for instance, the red stars and blue stars are distributed across a given area of the sky. It has been used by Fritz Zwicky in the United States in studies of galaxies made with the 200-inch telescope. Zwicky has been interested in sorting out the stars of what seem to be two stellar 'populations'. Population I stars are the bright blue O and B stars and others that are found in the spiral arms of galaxies, while Population II stars are those that do not congregate around the plane of a galaxy. In Population I the brightest stars are blue, in Population II the brightest stars are red—the so-called red giants and super-giants. Zwicky has taken his photographs through blue and yellow filters. The blue filter gives preference to the stars of Population I, while the yellow filter gives preference not only to the red but also to the orange and yellow stars of Population II. For Population I distribution he combines a blue-light negative that gives the Population I areas as black with a yellow-light positive in which the Population II areas are white. When they are printed together, the Population II areas do not show up because they appear black against the black sky, but the Population I areas show up clearly (Pl. XA, left). Using a yellow-light negative with a blue-light positive the Population II areas show up very clearly (Pl. XA, right).

Another photographic technique that has come into use is the 'composite' picture. Here a print is made using a number of negatives, one after the other. Its main purpose is to show all kinds of evidence on one picture, or to build up a satisfactory picture of a planet from a series of less satisfactory negatives. This is not ideal for planets, which have always been difficult to photograph. The air moves the image about and so spoils the fine detail on them. It is here that the visual observer has always had the advantage. Looking through his telescope and using just those moments when the image is steady, he can build up a detailed

drawing, even though it may take him a long time to do so. The composite picture is one way to try to get over the problem, but it seems that the most promising results are likely to come from the use of electronics. At the moment experiments are along two lines: the use of an 'electron camera' on the one hand, and of a special television camera on the other.

The television camera technique sounds simple in principle, for the camera is placed at the eyepiece end of a telescope instead of the ordinary photographic plate (Pl. XB). The resulting image passes to a closed-circuit television equipment and is finally displayed on a cathode-ray (or television) screen. Now all television pictures, whether on a closed circuit or an ordinary broadcast, are crossed by horizontal lines. This is because the pictures are built up by scanning with a bright spot back and forth across the picture area, and lines are thus unavoidable. However, although these lines limit the detail that can be seen, the television camera has advantages that make it likely to become a much used technique. The main one of these is that the final cathode-ray screen picture can be made as bright as desired so that it can be photographed quickly and easily. So if the picture is that of a planet, an observer can wait for a moment when the air is clear and steady—a moment of 'good seeing', as it is usually called—and then take a photograph which, because it does not require a long exposure, can use this good seeing to full advantage (Pl. XI).

Electronic methods, like the television camera, have other advantages besides that of a bright final image. By appropriate electronic circuits, astronomers can arrange to alter the contrast between bright and dark areas of the picture, and in this way suppress unwanted light. The dark night sky always has a dim glow that shows up in very long-exposure photographs; being able to suppress this is a great advantage, for it makes it possible for astronomers to detect very dim objects indeed. In addition, the kind of 'photo-electric' materials that are used in a television camera to convert light into electric current operate from radiation over a wider range of the spectrum than photographic materials. In theory, they are also more sensitive and so can respond to much fainter illumination, although techniques need to be much improved before this advantage can be usefully employed.

The electron camera is actually a special television camera with

a built-in photographic plate. Its general layout is shown in Fig. 25. The whole instrument is contained in a glass covering from which the air has been pumped out. At the top of this covering the glass is ground extremely flat, and light from the telescope can pass through to the photo-electric material. This emits electrons that pass down between electrified plates which act like an electronic lens and focus the electrons on to a photographic plate near the bottom of the camera. A magazine of spare plates is also kept there and they are brought into use by a magnetic control coil on the outside of the tube. The photo-electric material is kept sealed in its own special holder until all is ready for use, when the holder is broken by a little hammer inside the camera, and the photo-electric material is moved under the optical image from the telescope. This ensures that no particles from the photographic plates can reach the photo-electric material before exposure and so cause it to be chemically damaged. The electron camera has to be kept very cold while operating, and has a flask of liquid air fitted to it. Invented by Professor André Lallemand of Paris, it is a complicated piece of equipment that has, however, already produced useful results in photographs of planets, stars and spectra. Its future development looks like being most worthwhile (*see* Pl. XII).

The electron camera uses special photographic plates designed to make a picture from electrons that fall on them, rather than from light. Other special plates have also been developed and used with much success in the very low frequency, long wave-length, end of the visible spectrum. Known as infra-red radiation, most of it is absorbed by the air around us, so that much of what the Sun and stars send out never reaches us. However, if we observe from a height of 1,800 feet or more, then the radiation does get through and photographs can be taken. Work of this kind is important because delving into new ranges of the spectrum will increase our knowledge about the nature of stars and conditions on the planets. Already some observations of this sort have been made in France and in South Africa at observatories that are well above the 1,800 feet level. Using specially designed equipment in both cases, spectra have been taken of infra-red sunlight reflected back to us from Venus and of infra-red radiation from the strange star Eta Carinae. Some lines which have been discovered in that star's spectrum may well give astronomers the clue they need to

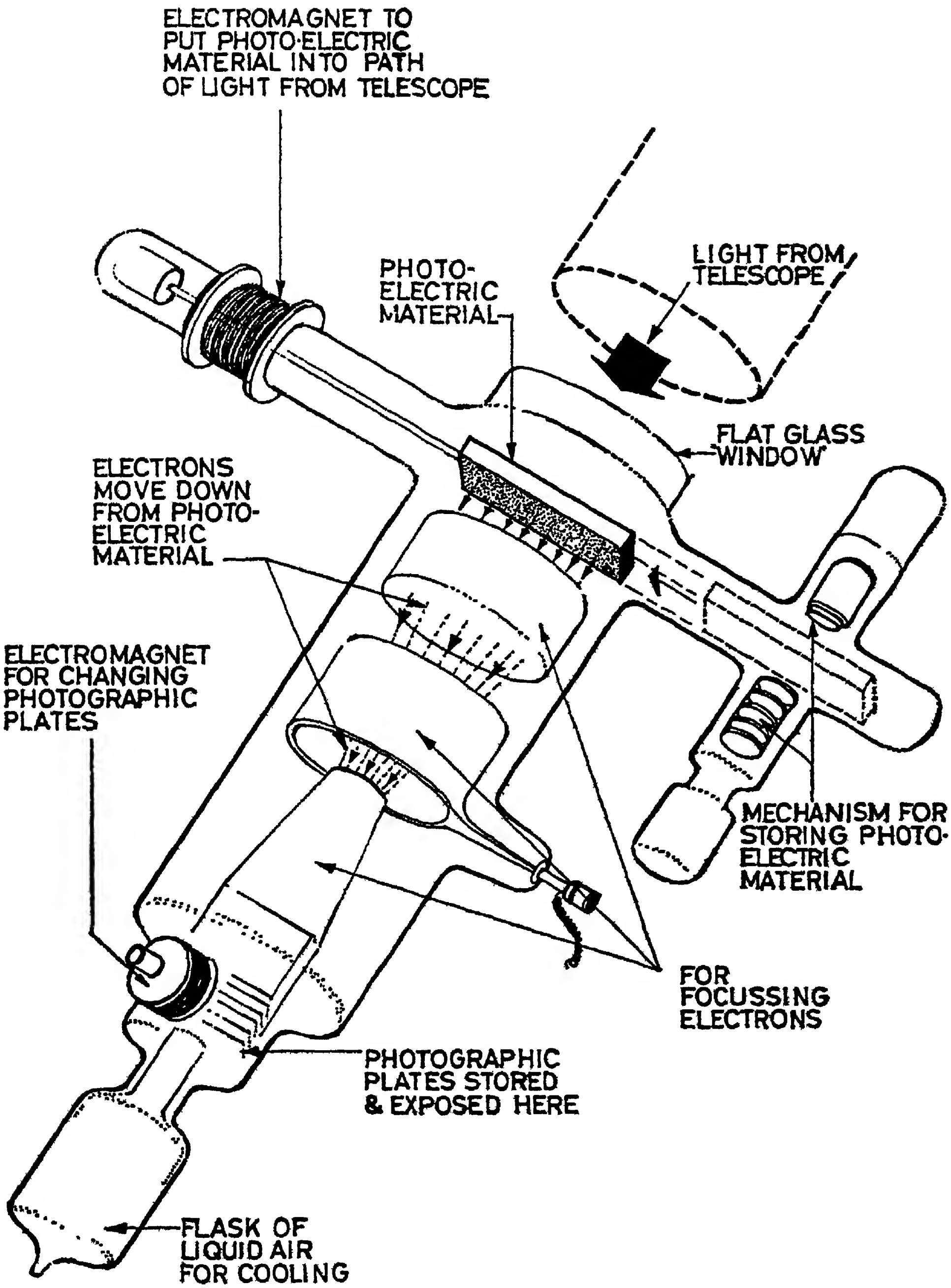


Fig. 25. Electron camera.

solve its peculiar behaviour; it was a naked-eye object in 1823, a really bright star in 1838, but since that time has sunk in brightness until now a telescope must be used to see it at all. As far as Venus is concerned, the observations have shown that the gas carbon dioxide is present in strong concentration, as some astronomers believed, and also that carbon monoxide is present, a fact that was not previously known. Of course, these are only the first results of the new techniques, but they certainly promise well for the future.

The astronomers who have been carrying out observations on the infra-red part of the spectrum have been able to work from observatories high above sea-level. But to extend observations into the part of the spectrum beyond the violet is a more difficult matter. This is because the air around us absorbs nearly all this ultra-violet radiation, as well as the even higher frequency X-rays and gamma-rays that come to us from the Sun and from other bodies in space. It is just as well for us as human beings that the air does act as a filter and keeps these deadly radiations away, but for astronomers it is very frustrating not to be able to observe them. These short-wave, high frequency radiations must be observed if the conditions on stars are to be more accurately known, and this is especially true of very hot bright stars like those of type O which emit ultra-violet radiation more strongly than visible light. To make worthwhile observations, astronomers or their equipment must rise above the Earth's atmosphere—or at least the thick parts of it. Recently all kinds of ways of doing this have been tried.

One way is to use balloons to carry equipment up to a suitable height. In France, Audouin Dollfus has ascended in a globe-shaped gondola carried to a height of some ten miles by a string of small hydrogen balloons (Pl. XIIIA). Inside his gondola, which is pressurized so that he does not need to wear breathing apparatus, Dollfus has carried out many observations and even taken motion pictures of certain phenomena. Photographs that he has obtained make it clear that even at this height much useful work may be done on the ultra-violet spectrum of the Sun and stars. Incidentally, Dollfus's work has also made it clear to astronomers that good planetary photographs can be obtained from such heights. The reason for this is that at heights like ten miles the atmosphere is

about ten times thinner than near the ground, so that winds and currents of air do not affect the image in a telescope to anything like the same degree.

Both of these factors—the observations of short-wave radiations and the ability to take satisfactory planetary and other photographs—have made astronomers look more closely into the use of telescopes carried to great heights by balloons. Professor Martin Schwarzschild and his colleagues at Princeton University in the United States have used large plastic balloons to carry equipment up to a height of fifteen miles or more. They began in 1957 by sending up a reflecting telescope with a mirror twelve inches across. This took motion pictures, but in later flights still photographs have been taken. The equipment in its latest form is quite complicated, for in addition to a telescope it contains a television camera and transmitter, as well as a radio control equipment. With all this apparatus, not only can the telescope be under remote control from the ground, but also whatever the telescope is seeing can be watched. Photographs are taken on board the balloon with the camera operated from the ground (Pl. XIIIB).

Professor Schwarzschild's results with project Stratoscope, as it has been named, have been remarkably successful, and a larger reflecting telescope with a 36-inch mirror is now being used. As with photographs from Dollfus's gondola, those of the Stratoscope are exceptionally clear, and close-ups of sunspots have surprised all astronomers by the detail that they show. Some previous photographs taken from the ground have shown the 'granulation' of the main gaseous body of the Sun, but never before has this been seen so clearly. These photographs now show that the 'granules' of hot gas are all of quite different sizes—useful information for the astronomer who is working out precisely the way in which radiation passes from the inside of the Sun to its outer layers. There seems no doubt, then, that this very high altitude observing can bring the astronomer many new and important facts (*see* Frontispiece).

Since 1957 new ways of observing the stars have developed in the form of space probes. Rockets and space travel have been the province of the story-teller ever since the time of Jules Verne, a hundred years ago but, with the launching of the first Sputnik in October 1957, space observations became a real possibility. The

original probes were put into orbit for studies of the upper parts of the Earth's atmosphere, but since then some astronomical work has been carried out, and much more is planned.

The Sun, being by far the nearest star to us, has come in for a good deal of study, and rockets and probes have produced some very exciting results. By fitting a special spectrograph inside a rocket and recovering the instrument later by parachute, the Sun's spectrum has been photographed well into the ultra-violet. The results have shown astronomers that the Sun generates much ultra-violet radiation in a layer of hydrogen gas that lies just above its main gaseous body. Pl. XIVA is a photograph taken in ultra-violet by another rocket—an Aerobee-Hi—carrying a camera on board. From this it can be seen that the radiation does not come evenly from all over the Sun but is emitted in patches. Other photographs have shown astronomers that the positions of these patches change from day to day and even from hour to hour. Photographs have also been taken from a rocket by the X-rays that the Sun sometimes sends out in great quantities (Pl. XIVB). British rockets launched from Woomera in Australia have also carried X-ray detectors. All these observations have shown astronomers that the Sun emits its X-rays in bursts, and then only when there is a sudden escape of light and ultra-violet radiation as well from deep inside the Sun. Some astronomers think that the X-rays are generated high up in the Sun's atmosphere, but further observations will doubtless help to decide the matter.

Rocket space probes can bring the astronomer much new knowledge, but their lives are only a few minutes long. Orbiting probes like the Luniks and Mariner II can make much more detailed observations, and both have provided many new facts. Perhaps the most famous is Lunik III, which took photographs of the far side of the Moon, which is never visible from the Earth. But Mariner II has probed the conditions on the planet Venus and its results have been of great interest, even if rather puzzling in many ways. They have, however, shown astronomers that the surface of the planet seems to be much hotter than they ever imagined (Pl. XV).

The use of artificial satellites with their own telescopes is already beginning, and it seems as though astronomers will soon have a number of orbiting astronomical observatories to help them

to unravel the mysteries of the universe. Certainly it does not seem as if it will be so very long before they have a telescope on the Moon. Here, with no atmosphere to act as a filter, the telescope could study the short-wave radiations that the stars and galaxies emit and bring the astronomer facts that he has never before been able to obtain. Indeed, the way ahead for optical astronomers looks every bit as full of excitement and promise as it does for those who are using radio telescopes to probe space.

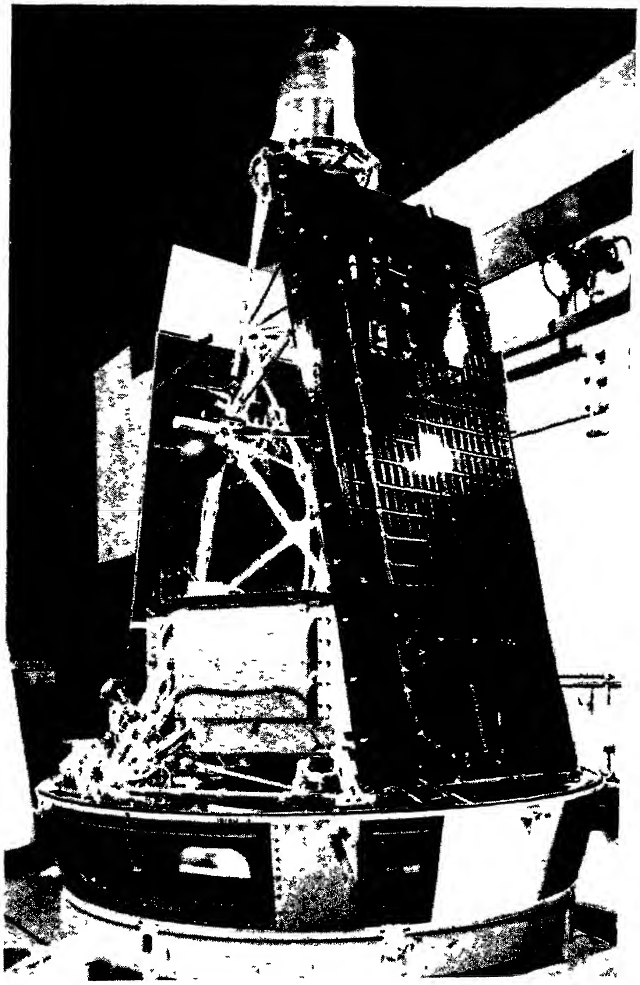
VI. Careers in Astronomy

To enter astronomy professionally requires a university degree. At school the important thing is to become proficient at mathematics—both pure and applied—and also to take a keen interest in every branch of physics, because both subjects will provide a sound background for all later work. The various universities have their own entrance requirements; your Careers Teacher or Head Teacher will no doubt be able to explain exactly what is needed.

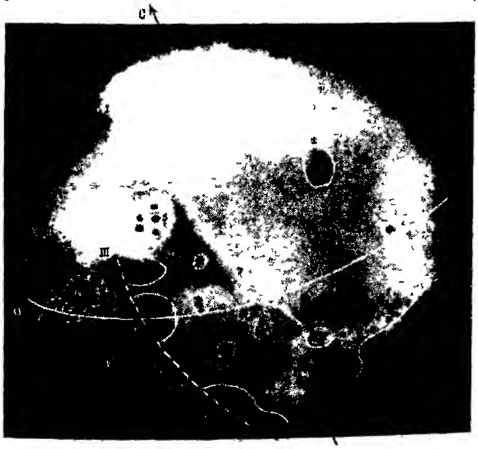
London University grants a degree in astronomy, but in most universities the subject is one that is studied after a first degree has been obtained. In both cases a degree must lay a good foundation. Some ability in mathematics is essential. Indeed, you can specialize in mathematics and read for a mathematics degree. This can lead to a career on the theoretical side of astronomy. In such a case you might be concerned with computing tables of stellar and planetary positions, or you might be doing work on the theory of the physics of stars or even, perhaps, studies connected with the origin and nature of the universe.

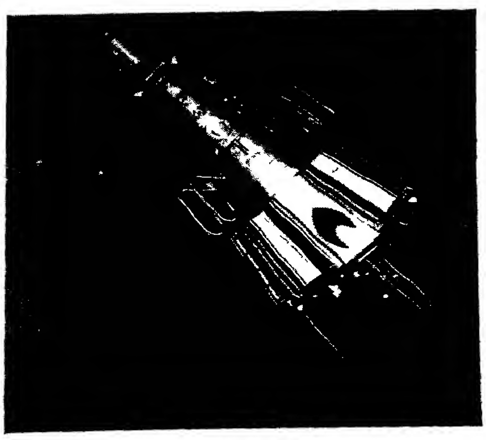
The other road to a career in astronomy is a good training in physics. A leaning towards atomic physics and spectroscopy can lead to work in astrophysics (the physics of stars, nebulae and galaxies), while an inclination to optics and electronics could lead to the development of new observing techniques and work over a wide range of problems. A student can, of course, specialize in radio and electronics and then carry out research in radio astronomy, although even here it is best to have a good general physics background, for radio astronomers have to do much of their work in co-operation with optical astronomers.

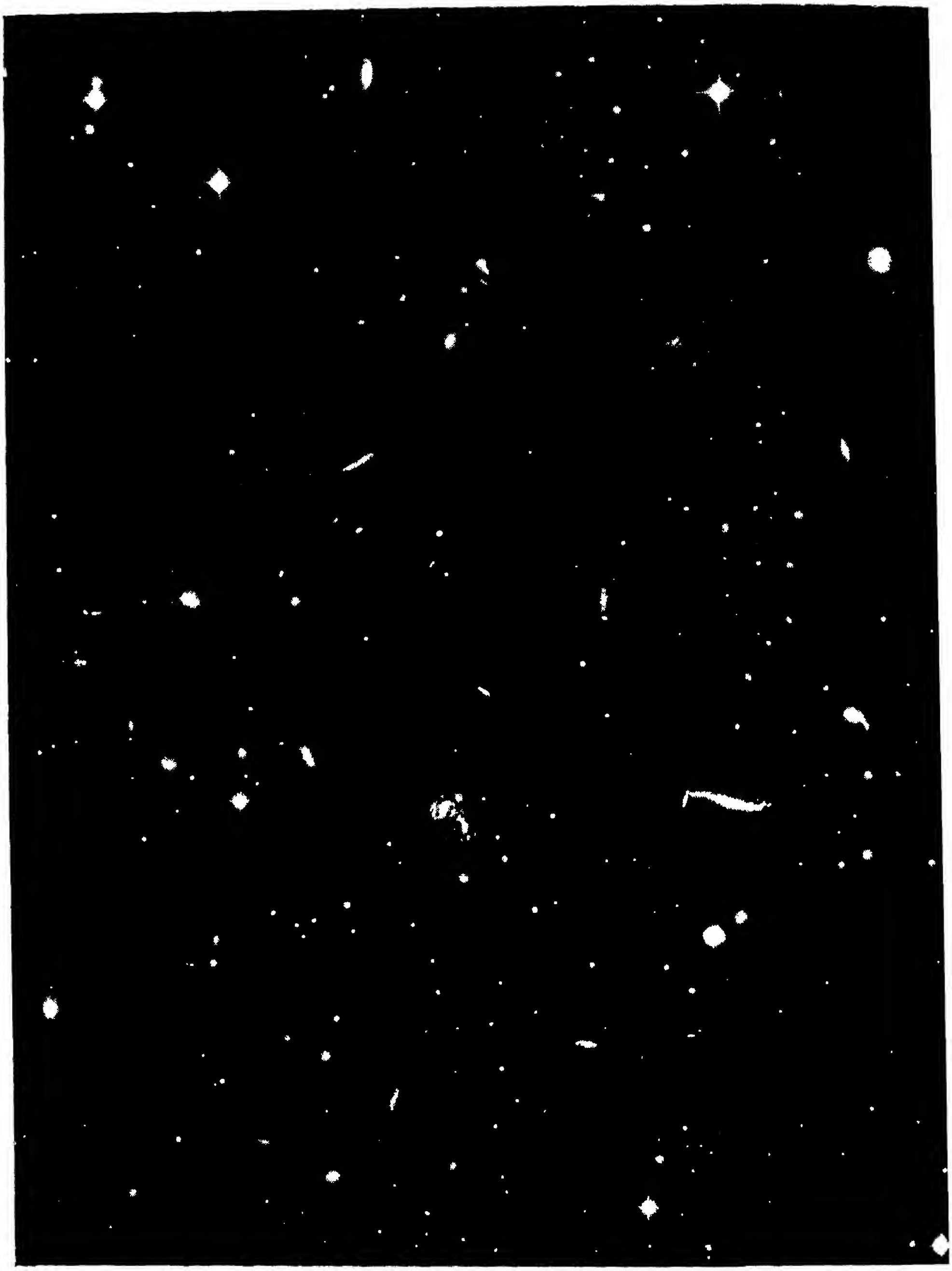
When once a degree is won, there are two possible ways of becoming a professional astronomer. The first is to obtain a post at either of the two British national observatories—the Royal Greenwich Observatory at Herstmonceux, Sussex, or the Royal Observatory, Edinburgh—through the Civil Service Commission



XV *Right*, the probe Mariner II folded ready for nose cap cover and launching. *Below, left*, the far side of the Moon photographed from the space probe Lunik III (*below, right*).







XVI A cluster of very distant galaxies, light from which has taken at least 3,000 million years to reach us.

at 6 Burlington Gardens, London, W.1. The other is to move into a university research department. You could choose a department where research in theoretical astronomy is being carried out, or go to work at a university observatory. Which you do will probably depend on what is available at the university where you have taken your degree, and so if you are keen to work in an observatory it is as well to seek admission in the first place to a university that possesses an astronomical observatory of its own. But to whatever university you go, the professor and his staff will be the best people with whom to discuss your wishes and the future. There is certainly much work to be done in astronomy and many research problems for a physics or maths graduate to tackle.

Finally, for those who may find it impossible to go to a university, there are some posts at observatories for technicians. This can be interesting work, especially co-operating with research astronomers in designing new apparatus for special investigations. A sound technical training, especially in either electronics or in mechanical engineering, is required. Towards the end of your training period, entry into an observatory should be discussed with the principal of your department at Technical College. Except for the Royal Greenwich Observatory, all observatories in Great Britain are situated in towns that have universities.

Astronomy is a science in which the amateur can still do useful work. Of course there are only certain kinds of work that can usefully be done, and the amateur must learn his subject carefully. Even so, studies of the surface features of the Moon and of the planets, especially Jupiter and Saturn, can be very worthwhile. Variable stars also offer a profitable field of work for some amateurs, while others spend their time searching for new comets and can achieve success if only they will persevere. Other amateurs who are mathematically minded compute the paths of comets and calculate details of observations to check the Moon's position in the sky. Some have even built their own radio telescopes, and carry out useful work with them. But whatever is done cannot be carried out alone. Guidance and co-operation are needed, and anyone desiring to undertake such research should, in the first instance, contact the Assistant Secretary of the British Astronomical Association at 303 Bath Road, Hounslow West, Middlesex, with a view to membership.

Some More Books to Read

CHISNALL, G. A., AND FIELDER, G.: *Astronomy and Spaceflight* (Harrap, 1962). 21*s.*

GAPOSCHKIN, C. PAYNE: *Introduction to Astronomy* (Methuen, 1961). 12*s* 6*d.*

LYTTLETON, R. A.: *The Modern Universe* (Grey Arrow Books, 1960). 3*s* 6*d.*

MOORE, PATRICK: *Guide to the Stars* (Eyre & Spottiswoode, 1960). 21*s.*

—— *Space in the Sixties* (Pelican (A. 621), 1963). 4*s.*

RONAN, COLIN A.: *Changing Views of the Universe* (Eyre & Spottiswoode, 1961). 15*s.*

THACKERAY, A. D.: *Astronomical Spectroscopy* (Eyre & Spottiswoode, 1961). 18*s.*

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